DOE workshop on fire modeling - NUREG 1934

Frederick W. Mowrer, Ph.D., P.E.

Director

Fire Protection Engineering Programs

Cal Poly - SLO

805-756-7834 office

fmowrer@calpoly.edu

NRC/EPRI workshops

- Dates for 4.5 day workshops at NRC this year
  - August 18-22, 2014
  - September 29-October 3, 2014
- Modules
  - 1 – PRA
  - 2 – Electrical analysis
  - 3 – Fire analysis
  - 4 – Human reliability analysis
  - 5 – Advanced fire modeling

Advanced Fire Modeling

- Course Objectives
  - Fire modeling for nuclear power plant (NPP) applications
  - Fire modeling uncertainty estimation
- Approach
  - Evaluate fire scenarios relevant to NPPs
  - Use models evaluated in verification and validation (V&V) study
  - Demonstrate capability and limitations of each model type
  - Quantify uncertainty as part of the fire modeling analysis
  - Identify relevant sensitivity analyses to support use of results

Background

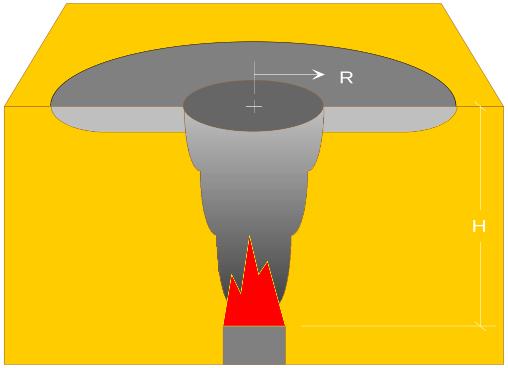
- NFPA issued the first edition of NFPA 805 in 2001
- NRC amended 10 CFR 50.48(c) in 2004 to employ NFPA 805 as alternative to existing deterministic requirements
- NFPA 805 requires that
  - Fire models shall be verified and validated (section 2.4.1.2.3)
  - Only fire models that are acceptable to the authority having jurisdiction (AHJ) shall be used in fire modeling calculations (section 2.4.1.2.1)
- NRC/RES and EPRI completed V&V project for five fire modeling tools in 2007
  - Results documented in NUREG-1824

NUREG 1934

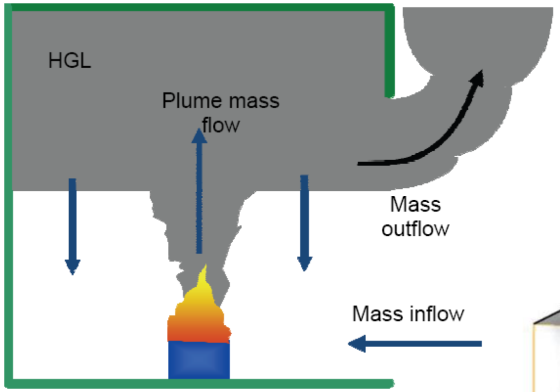
- Describes the process of conducting fire modeling analyses for commercial NPP applications
- The process addresses the following technical elements
  - Selection and definition of fire scenarios
  - Determination and implementation of input values
  - Uncertainty quantification
  - Sensitivity analysis
  - Documentation
- The document provides generic guidance, recommended best practices, and example applications

Fire models addressed in NUREG 1934

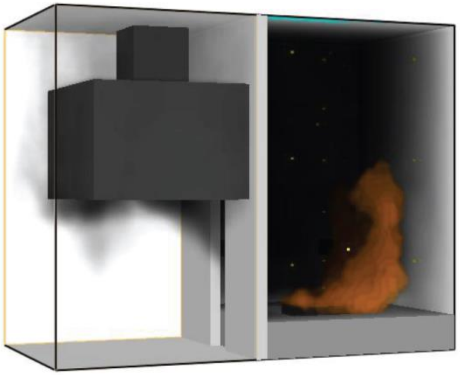
- Algebraic models (1.4.1)
  - FDTs
  - FIVE-rev1



- Zone models (1.4.2)
  - CFAST
  - MAGIC



- CFD models (1.4.3)
  - FDS



Fire modeling process

- Step 1 - Define modeling goals
- Step 2 - Characterize fire scenarios
- Step 3 - Select fire models
- Step 4 - Calculate fire conditions
- Step 5 - Sensitivity / uncertainty
- Step 6 - Document the analysis

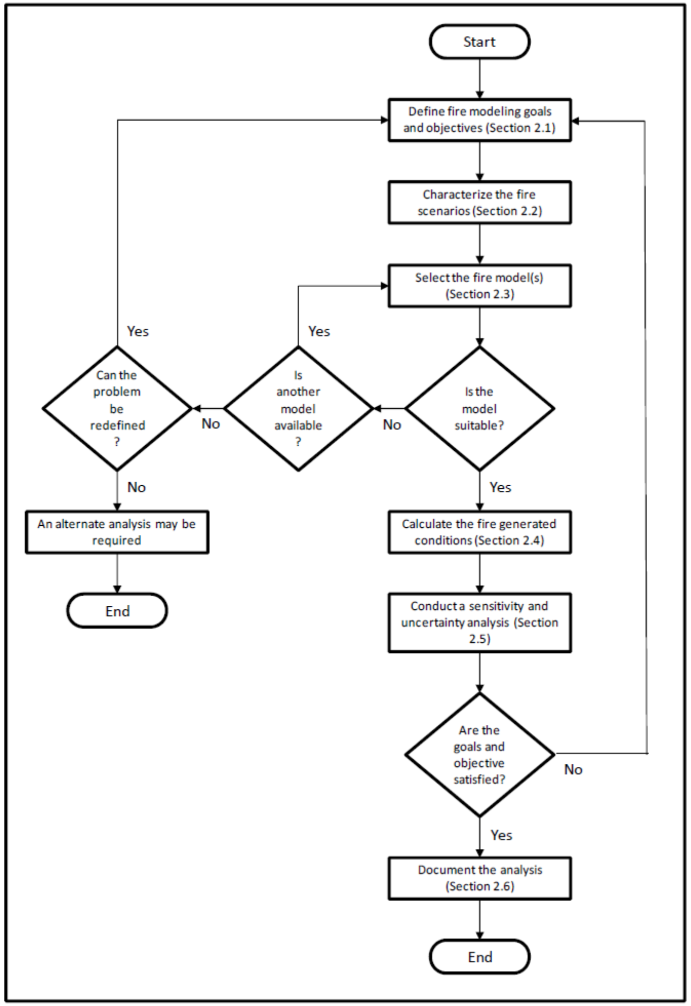


Figure 2-1. Fire modeling process.

Step 1 –
Define Modeling Goals

- Establish goals and performance objectives for the fire modeling application
- Example of a goal
  - Demonstrate that targets required for safe shutdown remain free from fire damage (deterministic goal) … to a specified level of probability (probabilistic goal)
- Example of a performance objective
  - Evaluate if a fire in Fire Area “X” involving Panel “Y” could cause the surface temperature of Cable “Z” to exceed 330 °C (625 °F)

Step 1 – Define Modeling Goals

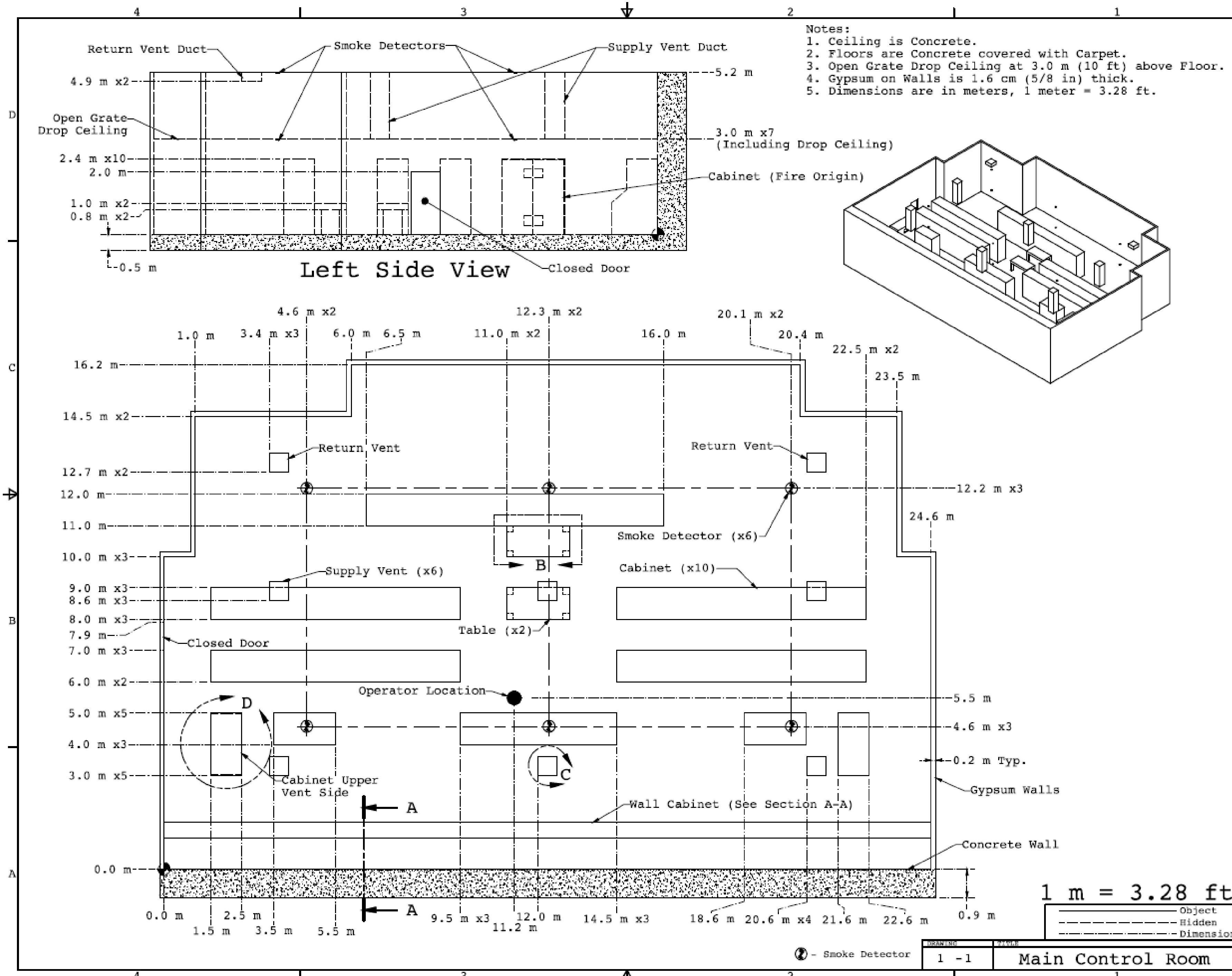
- Maximum acceptable surface temperature for a cable, component, secondary combustible, structural element, or fire-rated construction
- Maximum acceptable incident heat flux for a cable, component, structural element, or secondary combustible
- Maximum acceptable exposure temperature for a cable, component, structural element, or secondary combustible
- Maximum acceptable enclosure temperature
- Maximum smoke concentration or minimum visibility
- Maximum or minimum concentration of one or more gas constituents, such as carbon monoxide, oxygen, hydrogen cyanide

Step 2 – Characterize Fire Scenarios

- A fire scenario is the set of elements needed to describe a fire incident
- These elements include the following:
  - Enclosure details
  - Source fire
  - Fire location within the enclosure
  - Fire protection features that will be credited
  - Ventilation conditions
  - Target location(s)
  - Secondary combustibles

Step 2 –
Characterize Fire Scenarios

- **Enclosure details**
  - The identity of the enclosures included in the fire model analysis
  - The physical dimensions of the enclosures
  - The boundary materials of each enclosure


Notes:
1. Ceiling is Concrete.
2. Floors are Concrete covered with Carpet.
3. Open Grate Drop Ceiling at 3.0 m (10 ft) above Floor.
4. Gypsum on Walls is 1.6 cm (5/8 in) thick.
5. Dimensions are in meters, 1 meter = 3.28 ft.
Return Vent Duct
Smoke Detectors
Supply Vent Duct
4.9 m x2
5.2 m
Open Grate Drop Ceiling
3.0 m x7 (Including Drop Ceiling)
2.4 m x10
2.0 m
Cabinet (Fire Origin)
1.0 m x2
0.8 m x2
0.5 m
Left Side View
Closed Door
4.6 m x2
12.3 m x2
20.1 m x2
1.0 m
3.4 m x3
6.0 m
6.5 m
11.0 m x2
16.0 m
20.4 m
22.5 m x2
23.5 m
16.2 m
14.5 m x2
Return Vent
Return Vent
12.7 m x2
12.0 m
12.2 m x3
11.0 m
24.6 m
Smoke Detector (x6)
10.0 m x3
B
Supply Vent (x6)
Cabinet (x10)
9.0 m x3
8.6 m x3
8.0 m x3
Table (x2)
7.9 m
Closed Door
7.0 m x3
6.0 m x2
Operator Location
5.5 m
D
5.0 m x5
4.6 m x3
4.0 m x3
0.2 m Typ.
C
3.0 m x5
Cabinet Upper Vent Side
Gypsum Walls
A
Wall Cabinet (See Section A-A)
Concrete Wall
0.0 m
A
0.0 m
1.5 m
2.5 m
3.5 m
5.5 m
9.5 m x3
11.2 m
12.0 m
14.5 m x3
18.6 m
20.6 m x4
21.6 m
22.6 m
0.9 m
1 m = 3.28 ft
Object
Hidden
Dimension
Smoke Detector
DRAWING
1 -1
TITLE
Main Control Room

Step 2 – Characterize Fire Scenarios

- **Source fire**
- The source fire is the forcing function for the fire scenario
- Common fuel packages include electrical panels and transformers, cables, transient combustible material, lubricant reservoirs, and motors
- The source fire is typically characterized by a specified heat release rate history
- Other important aspects include the physical dimensions of the burning object, its composition, and its behavior when burning

Step 2 –
Characterize Fire Scenarios

- **Recommended HRR values from NUREG CR-6850**

Table G-1
Recommended HRR Values for Electrical Fires

Ignition Source	HRR kW (Btu/s)		Gamma Distribution	
	75th	98th	α	β
Vertical cabinets with qualified cable, fire limited to one cable bundle	69 [1] (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Vertical cabinets with qualified cable, fire in more than one cable bundle	211 [2] (200)	702 [3] (665)	0.7 (0.7)	216 (204)
Vertical cabinets with unqualified cable, fire limited to one cable bundle	90 [4] (85)	211 [2] (200)	1.6 (1.6)	41.5 (39.5)
Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232 [5] (220)	464 [6] (440)	2.6 (2.6)	67.8 (64.3)
Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232 [5] (220)	1002 [7] (950)	0.46 (0.45)	386 (366)
Pumps (electrical fires) [8]	69 (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Motors [8]	32 (30)	69 (65)	2.0 (2.0)	11.7 (11.1)
Transient Combustibles [9]	142 (135)	317 (300)	1.8 (1.9)	57.4 (53.7)

Step 2 –
Characterize Fire Scenarios

- **Recommended HRR values from NUREG CR-6850**

Recommended values should be used with caution after determining if the cabinet in question meets the criteria for such values. A visual inspection of the cabinet internals should be very helpful for assessing the applicability of recommended fire intensities.

The recommended HRR profile for electrical cabinets is as follows

- The fire grows to its peak HRR in approximately 12 minutes.
- The fire burns at its peak heat release for approximately eight additional minutes.

This profile was obtained by averaging the growth times and steady burning durations of the Sandia cabinet experiments, listed in Table G-2.

Step 2 – Characterize Fire Scenarios

- **Fire location**
- The location depends on the fire modeling goal, the target location, and the fire modeling tool selected
- Examples:
  - Targets in the fire plume or ceiling jet
  - Targets affected by flame radiation
  - Targets engulfed in flames
  - Targets immersed in the Hot Gas Layer

Step 2 – Characterize Fire Scenarios

- **Credited fire protection**
- Fire protection features to be credited in a fire modeling analysis usually require a fire protection engineering evaluation of the system's effectiveness
  - Assessment of the system compliance with applicable codes, including maintenance and inspection
  - Assessment of the system performance against particular fire scenarios being considered.
- Fire modeling tools may not be able to model the impact of some of the fire protection features credited in a given scenario.

Step 2 – Characterize Fire Scenarios

- **Ventilation conditions**
  - Mechanical ventilation
    - Normal HVAC / purge mode
  - Natural ventilation
    - Door / window / damper / vent positions

- **Target location(s)**
  - The physical dimensions of the target relative to the source fire or the fire model coordinate system.

Step 2 – Characterize Fire Scenarios

- **Secondary combustibles**
- Any combustible materials that, if ignited, could affect the exposure conditions to the target set considered.
  - Intervening combustibles, which are those combustibles located between the source fire and the target, are examples of secondary combustibles
- Secondary combustibles include both fixed and transient materials
- Secondary combustibles take on the characteristics of a target prior to their ignition

Step 3 –
Select Fire Models

- Fire models can be classified into three groups:
  - Algebraic models
  - Zone models
  - CFD models
- The level of effort required to describe a scenario and the computational time consumed by each group increase in the order in which they are listed.
  - Combination of all three types of models may be useful for analyzing a specific problem.

Step 3 –
Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Algebraic models	FDT^{S} FIVE-Rev1	Screening calculations; zone of influence; target damage by thermal radiation, Hot Gas Layer, or thermal plume acting in isolation.	Simple to use; minimal inputs; quick results; ability to do multiple parameter sensitivity studies.	Limited application range; treats phenomena in isolation; typically applicable only to steady state or simply defined transient fires (e.g., proportional to the square of time or t^2 fires).

Step 3 –
Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Zone Model	CFAST MAGIC	Detailed fire modeling in simple geometries; often used to compute hot gas temperatures and target heat fluxes.	Simple to use; couples Hot Gas Layer and localized effects; quick results; ability to do multiple parameter sensitivity studies.	Error increases with increasing deviation from a rectangular enclosure; large horizontal flow paths not well treated.

Step 3 –
Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Computation Fluid Dynamics Model	FDS	Detailed fire modeling in complex geometries, including computing time to target damage and habitability (MCR abandonment or manual action feasibility).	Ability to simulate fire conditions in complex geometries and with complex vent conditions.	Significant effort to create input files and post-process the results; long simulation times; difficult to model curved geometry, smoke detector performance, and conditions after sprinkler actuation.

Validation parameters

Table 2-5. Summary of selected normalized parameters for application of the validation results to NPP fire scenarios (NUREG-1824/EPRI 1011999, 2007).

Quantity	Normalized Parameter	General Guidance	Validation Range
Fire Froude Number	$\dot{Q}^* = \dfrac{\dot{Q}}{\rho_\infty c_p T_\infty D^2 \sqrt{gD}}$	Ratio of characteristic velocities. A typical accidental fire has a Froude number of order 1. Momentum-driven fire plumes, like jet flares, have relatively high values. Buoyancy-driven fire plumes have relatively low values.	0.4 – 2.4
Flame Length Ratio	$\dfrac{H_f + L_f}{H_c}$ $\dfrac{L_f}{D} = 3.7\,\dot{Q}^{*\,2/5} - 1.02$	A convenient parameter for expressing the "size" of the fire relative to the height of the compartment. A value of 1 means that the flames reach the ceiling.	0.2 – 1.0
Ceiling Jet Distance Ratio	$\dfrac{r_{\mathrm{cj}}}{H_c - H_f}$	Ceiling jet temperature and velocity correlations use this ratio to express the horizontal distance from target to plume.	1.2 – 1.7

Validation parameters

Quantity	Normalized Parameter	General Guidance	Validation Range
Compartment Aspect Ratio	L/H_c or W/H_c	This parameter indicates the general shape of the compartment.	0.6 – 5.7
Radial Distance Ratio	$\dfrac{r}{D}$	This ratio is the relative distance from a target to the fire. It is important when calculating the radiative heat flux.	2.2 – 5.7
Equivalence Ratio	$\varphi = \dfrac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{O_2}}$ $\dot{m}_{O_2} = \begin{cases} 0.23 \times \frac{1}{2} A_0 \sqrt{H_0} & \text{(Natural)} \\ 0.23\ \rho_\infty \dot{V} & \text{(Mechanical)} \end{cases}$	The equivalence ratio relates the energy release rate of the fire to the energy release that can be supported by the mass flow rate of oxygen into the compartment, $\dot{m}_{O_2}$. The fire is considered over- or under-ventilated based on whether φ is less than or greater than 1, respectively. The parameter, r, is the stoichiometric ratio.	0.04 – 0.6

Step 3 – Select Fire Models

- Fire parameters may fall outside their validation range defined in NUREG-1824
- The predictive capabilities of the fire models in many scenarios can extend beyond the range
- Analyst is required to address these situations
- Sensitivity analyses can be used to address these scenarios

Step 4 – Calculate Fire Conditions

- This step involves running the model(s) and interpreting the results
  - Determine the output parameters of interest
  - Prepare the input file
  - Run the computer model
  - Interpret the model results
  - Arrange output data in a form that is suitable to address performance objectives

Step 5 - Sensitivity And Uncertainty Analyses

- A comprehensive treatment of uncertainty and sensitivity analyses are an integral part of a fire modeling analysis under NUREG-1934
- Model uncertainty
  - Models are developed based on idealizations of the physical phenomena and simplifying assumptions
- Parameter uncertainty
  - Many input parameters are based on available generic data or on fire protection engineering judgment

Step 6 – Document The Analysis

- Information needed to document fire scenario selection will be gathered from a combination of observations made during engineering walkdowns and a review of existing plant documents and/or drawings
  - Marked up plant drawings.
  - Design basis documents (DBDs).
  - Sketches.
  - Write-ups and input tables.
  - Software versions, descriptions, and input files.
- A reviewer should be able to reproduce the results of a fire scenario analysis from the information contained within the documentation

Representative Fire Scenarios

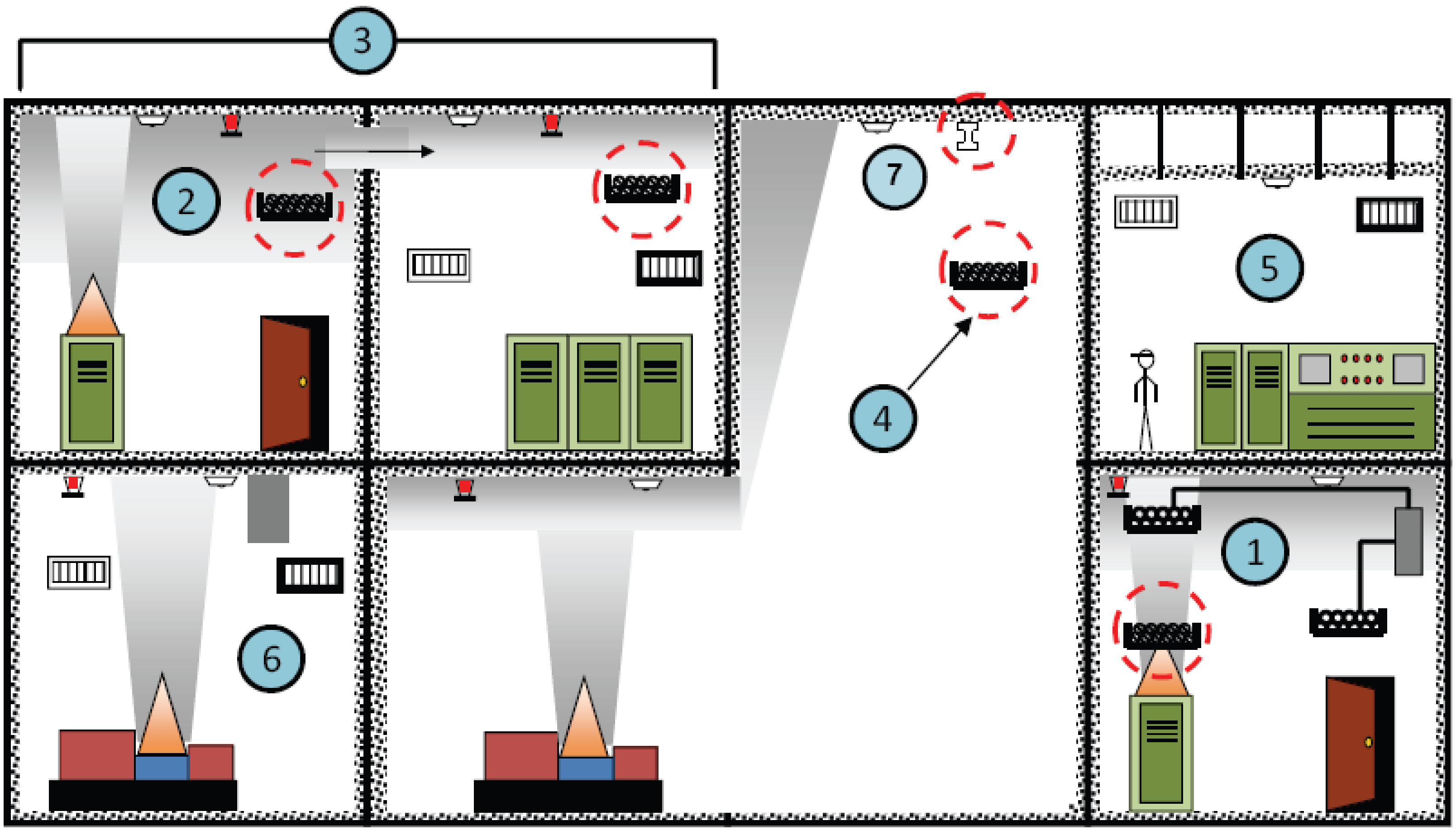


Figure 3-1. Pictorial representation of the fire scenario and corresponding technical elements described in this section.

Scenario 1 – Targets in the Flames or Plume

- This scenario consists of a target (electrical cable in a raceway) immediately above an ignition source (electrical cabinet)
- Objective: Calculate the time to damage for a target immediately above a fire
- Examples B and E

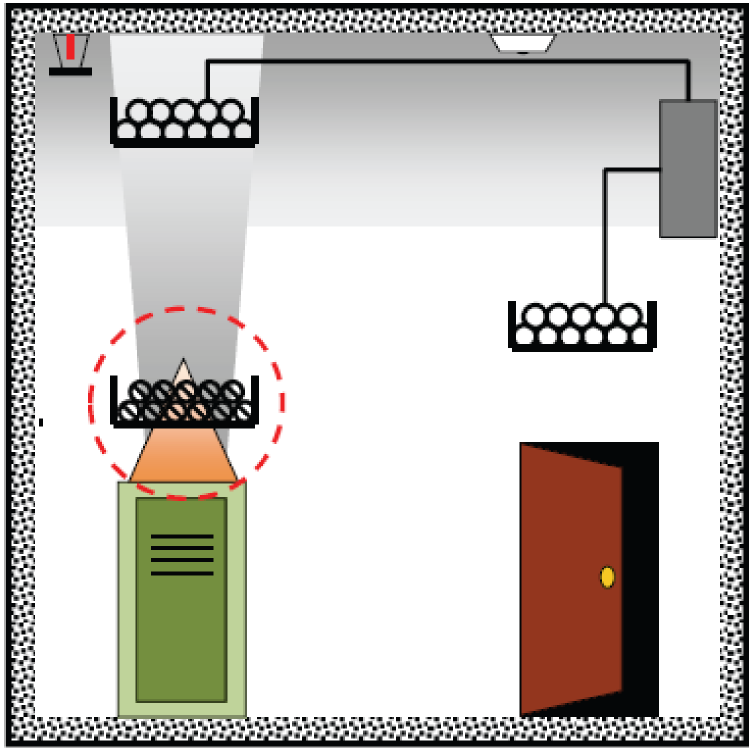


Figure 3-3. Pictorial representation of scenario 1

Scenario 2 – Targets Inside or Outside the Hot Gas Layer

- This scenario consists of a target, ignition source, and perhaps a secondary fuel source
- Objective: Calculate the time to damage for the target if it is inside or outside the Hot Gas Layer
- Examples C and E

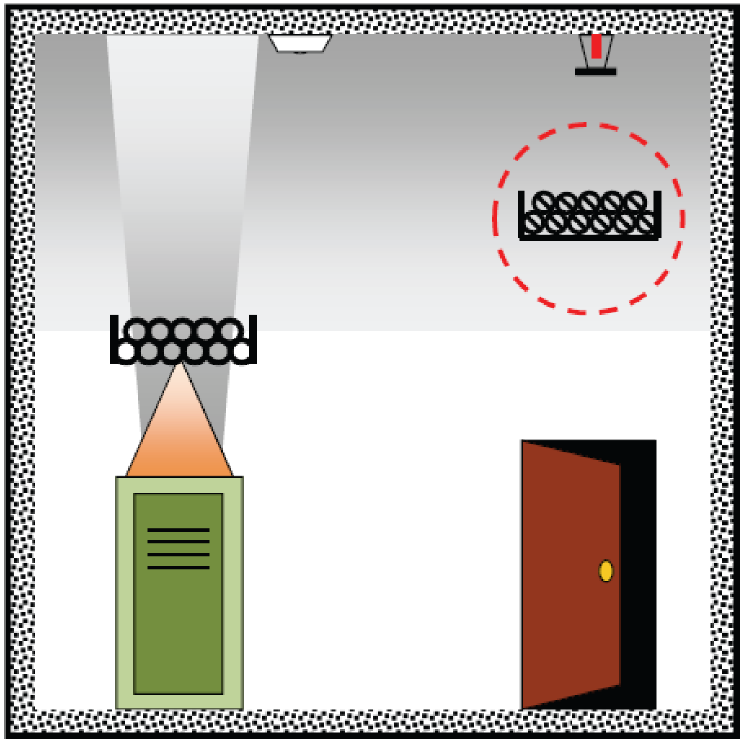


Figure 3-4 Pictorial representation of scenario 2

Scenario 3 – Targets Located in Adjacent Rooms

- This scenario consists of a target in a room adjacent to the room of fire origin
- Objective: Calculate the time to damage for a target in a room next to the room of fire origin
- Example G

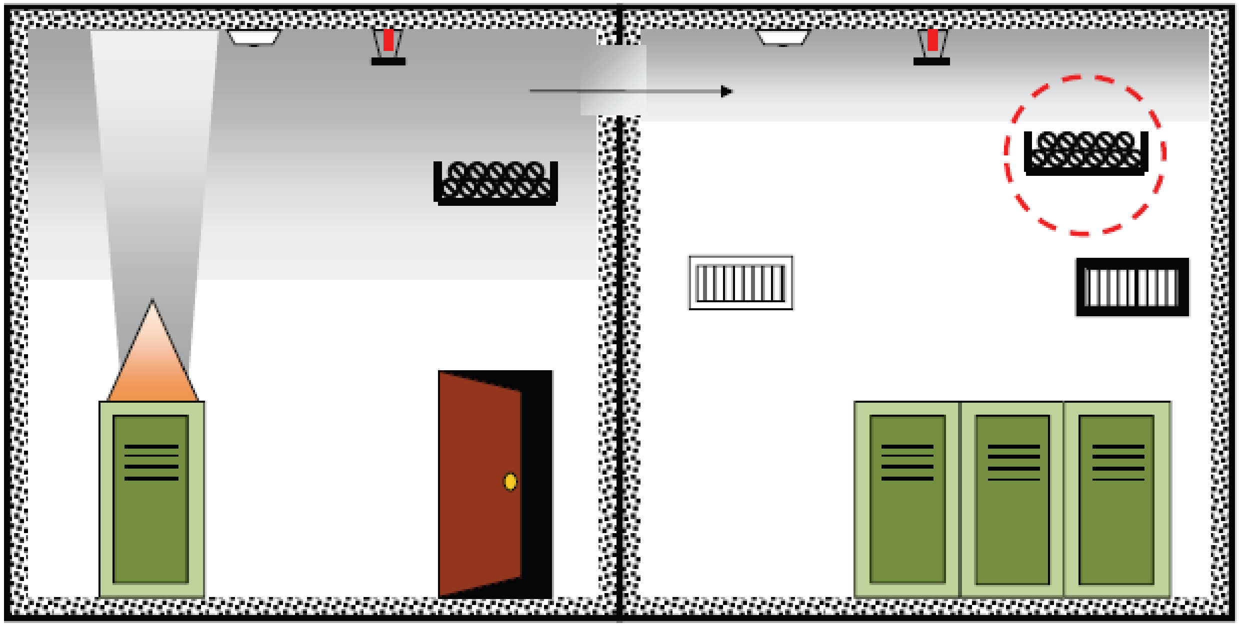


Figure 3-5. Pictorial representation of scenario 3

Scenario 4 – Targets in Rooms with Complex Geometries

- This scenario involves a room with an irregular ceiling height
- Objective: Calculate the time to damage for a target in a room with a complex geometry
- Examples D and H

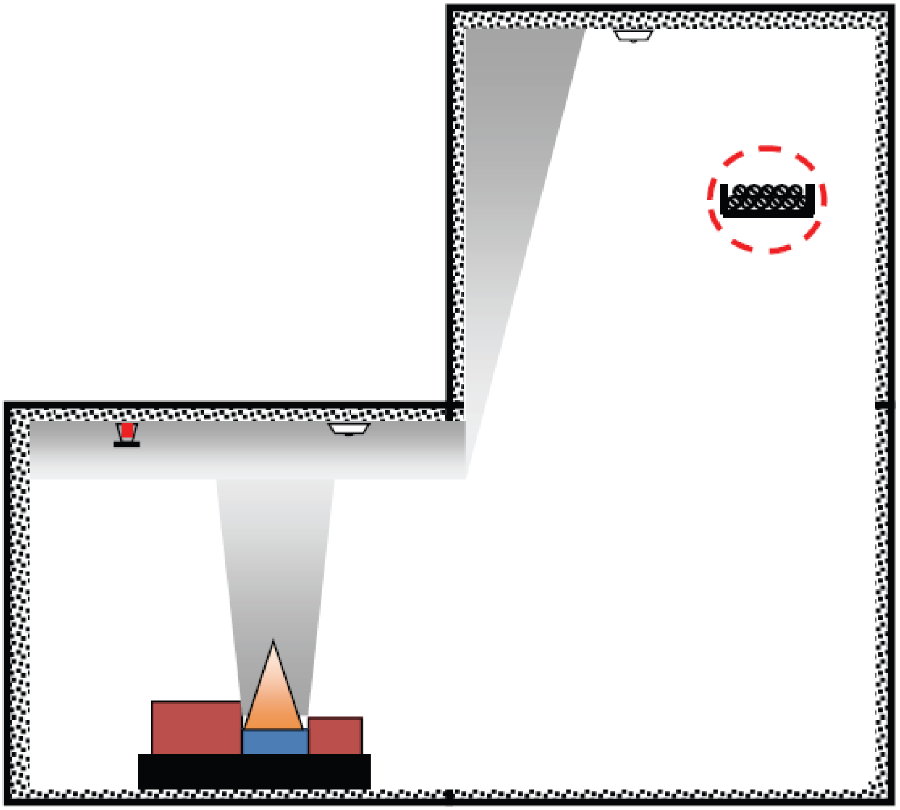


Figure 3-6. Pictorial representation of scenario 4

Scenario 5 – Main Control Room Abandonment

- This scenario consists of a fire (electrical cabinet fire within the main control board) that may force operators out of the control room
- Objective: Determine when control room operators will need to abandon the control room due to fire-generated conditions
- Example A

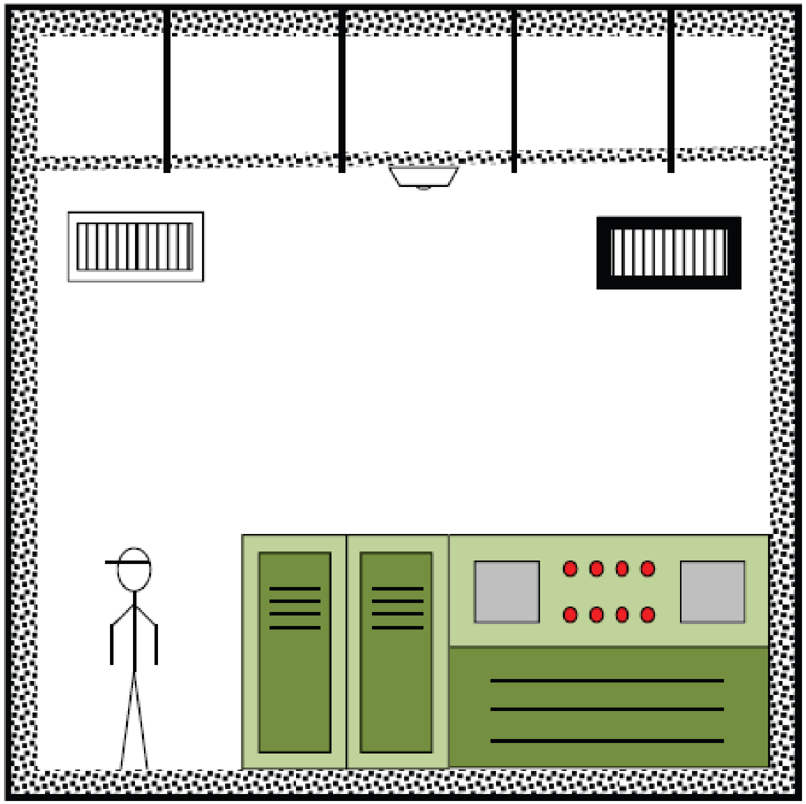
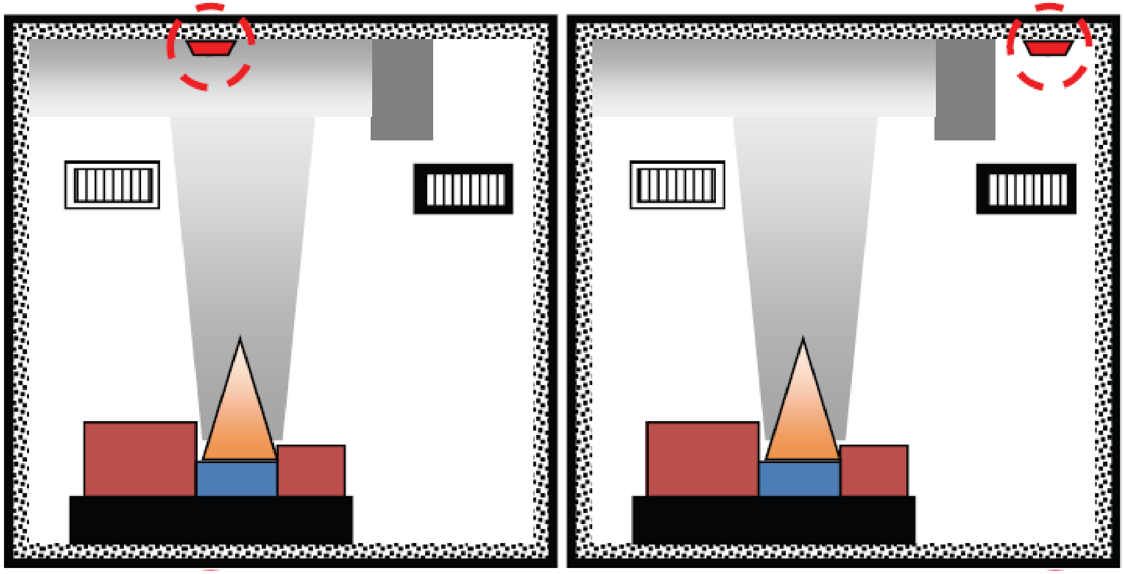


Figure 3-7. Pictorial representation of scenario 5

Scenario 6 – Smoke Detection and Sprinkler Activation

- This scenario addresses smoke/heat detector or sprinkler activation
- Objective: Calculate the response time of a smoke or heat detector that may be obstructed by ceiling beams, ventilation ducts, etc.
- Examples B and E



Scenario 7 – Fire Impacting Structural Elements

- This scenario consists of fire impacting exposed structural elements
- Objective: Characterize the temperature of structural elements exposed to a nearby fire source
- Example F

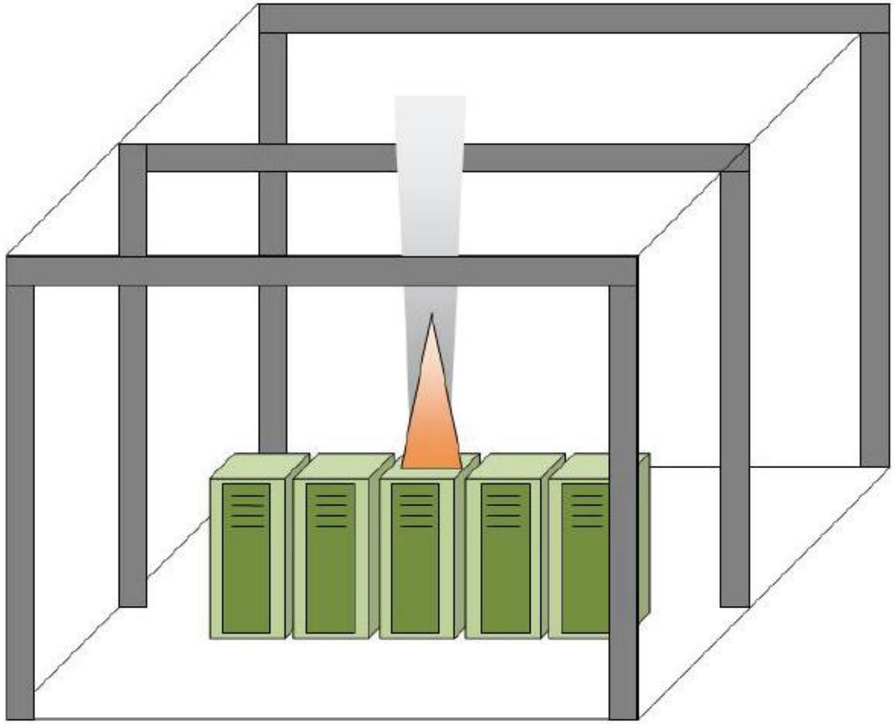


Figure 3-9. Pictorial representation of scenario 7

Summary of NUREG-1934

- The purpose of this discussion has been to introduce the following concepts relevant to NPP applications:
  - The fire modeling process
  - The fire modeling tools
  - Model validation parameters
  - Representative fire modeling scenarios
  - Uncertainty / sensitivity analyses

Fire Model
Verification and Validation

- ASTM E 1355, Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models
  - **Verification**: the process of determining that the implementation of a calculation method accurately represents the developer’s conceptual description of the calculation method and the solution to the calculation method. Is the Math right?
  - **Validation**: the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method. Is the Physics right?
  - This presentation focuses primarily on validation

Measurements/ Parameters

- Room Temperatures
  - Main control room abandonment study
  - Targets in room of fire origin or adjacent compartments
- Flame height, Plume & Ceiling Jet temperatures
  - Target heating and target temperature near the ignition source

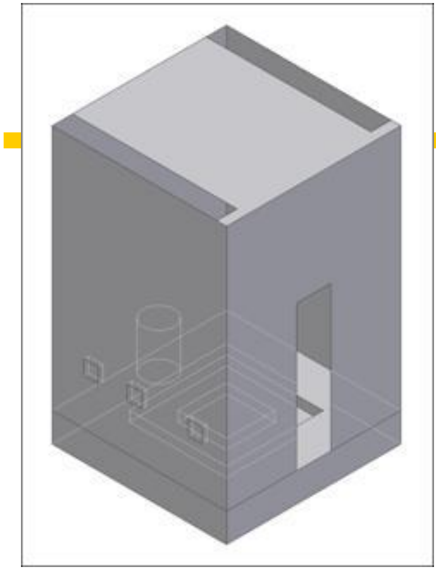
Measurements/ Parameters

- Oxygen & smoke concentration
  - Main control room habitability
- Room pressure
  - Issues related to mechanical ventilation and/or smoke migration
- Target/wall heating and target/wall temperature
  - Most fire scenarios throughout the plant

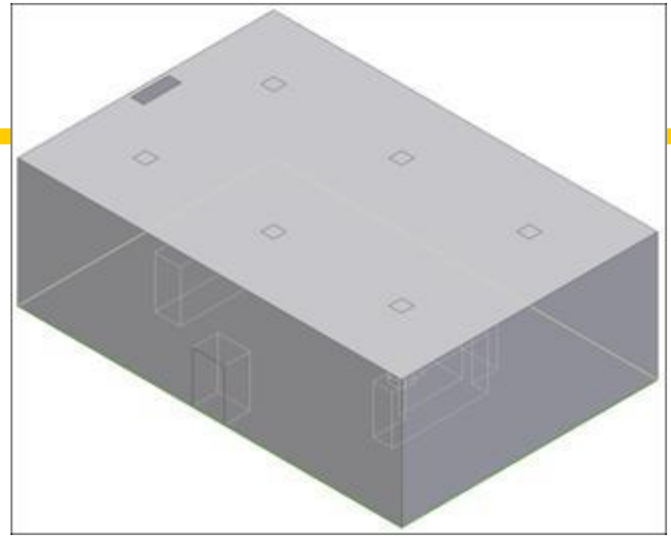
How were experiments selected?

- Selection Criteria: High-Quality Experiments
  - Large-scale experiments
  - Availability of data
  - Directly applicable to nuclear power plant applications
  - Accurate measurement of the fire heat release rate
  - Well documented
  - Uncertainty analysis useful
- Selection Process
  - Extensive review of fire literature
  - Scarcity of high-quality large-compartment fire test data
  - Typical industry tests: proprietary, reduced-scale, not NPP related

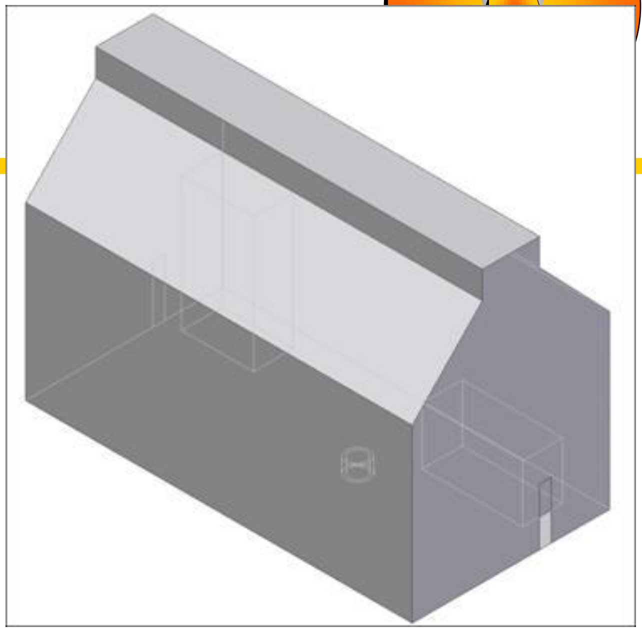
Pump Room
ICFMP BE #4, 5



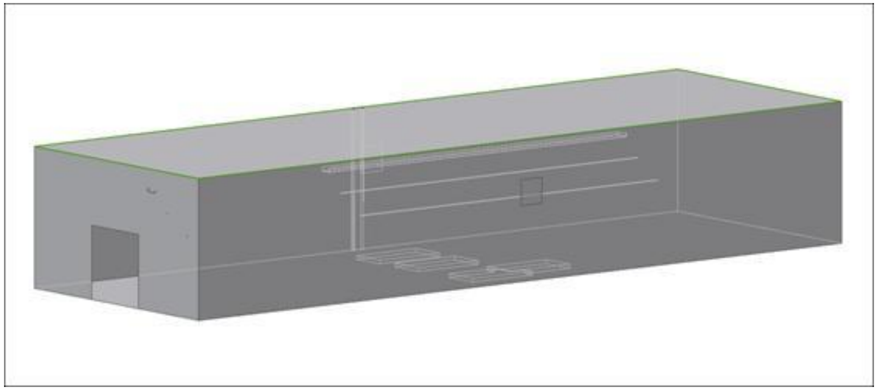
Main Control Room
FM/SNL



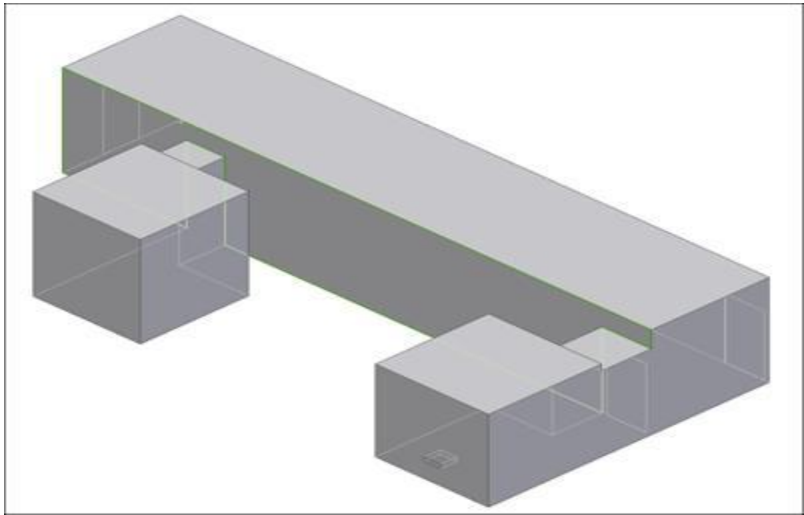
Turbine hall
ICFMP BE# 2



ICFMP BE# 3



NBS Multi-compartment



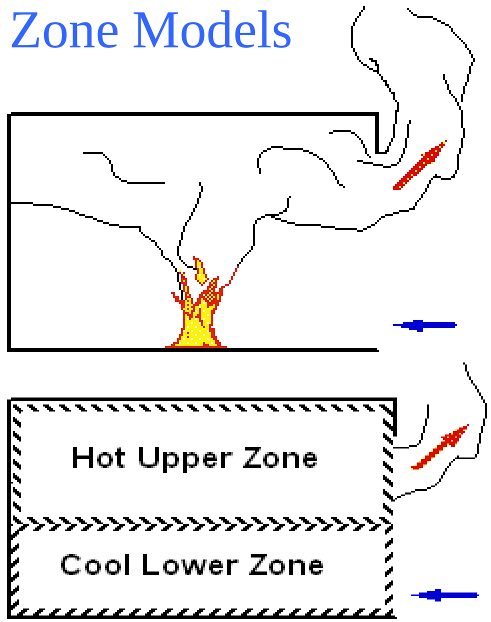
Fire models selected for validation study

Fire Dynamics Tools (FDT^{S})	NRC Spreadsheets
FIVE-Rev1	EPRI Spreadsheets
Cons. Fire & Smoke Transport (CFAST)	NIST zone model
MAGIC	Electricite de France zone
Fire Dynamics Simulator (FDS)	NIST CFD Model

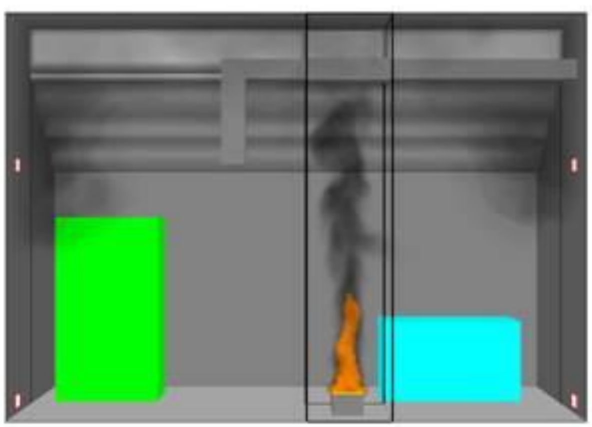
Spreadsheets

$$L_f = 0.23\dot{Q}^{2/5} - 1.02D$$

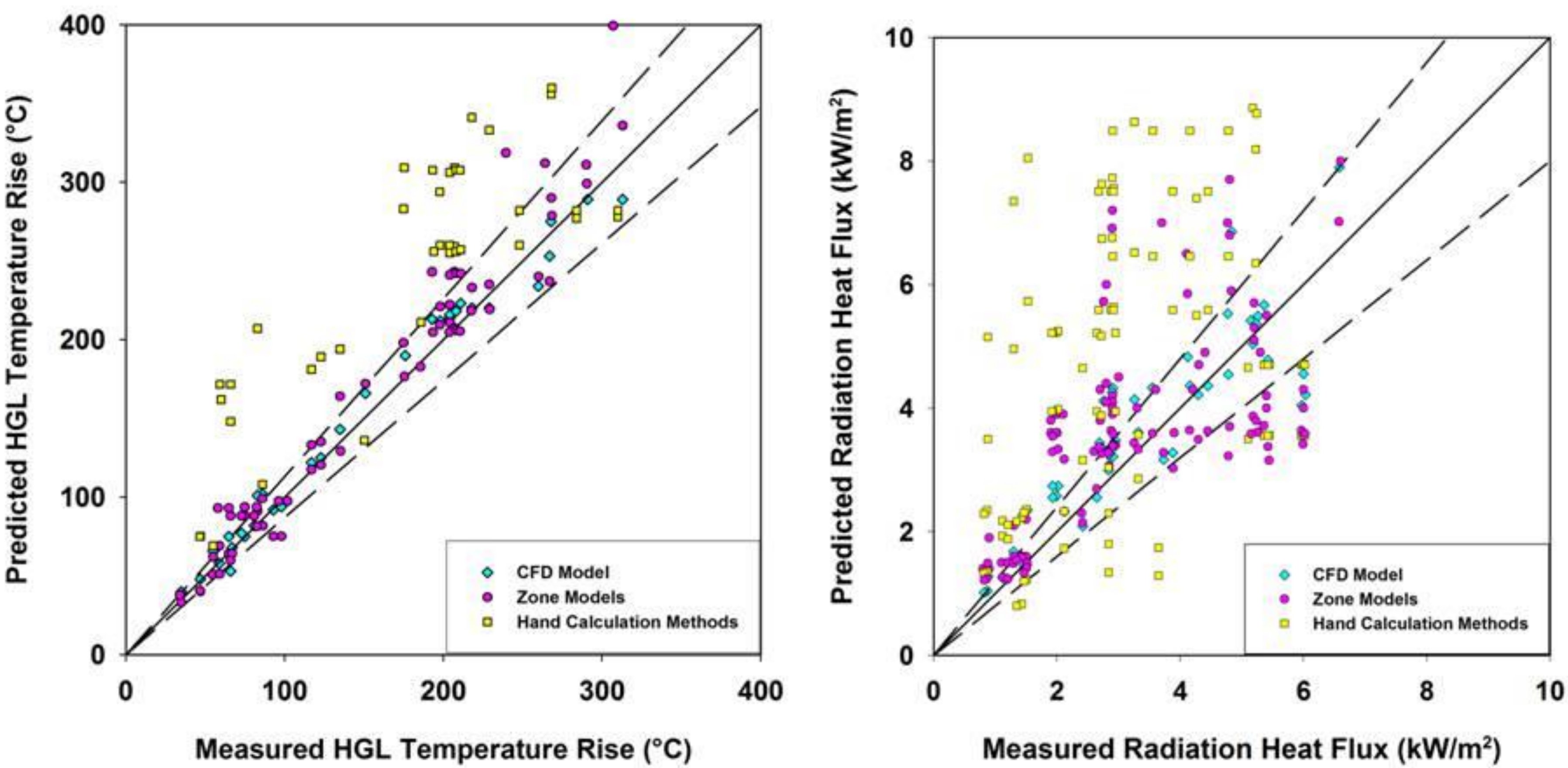
Zone Models



Field Models



Quantitative V&V Results



Measured vs. Predicted Hot Gas Layer Temperature Rise (left) and Measured vs. Predicted Heat Flux (right)

Results of the V&V

Parameter				Fire Model		
		FDT^s	FIVE-Rev1	CFAST	MAGIC	FDS
Hot gas layer temperature (“upper layer temperature”)	Room of Origin	YELLOW+	YELLOW+	GREEN	GREEN	GREEN
	Adjacent Room	N/A	N/A	YELLOW	YELLOW+	GREEN
Hot gas layer height (“layer interface height”)		N/A	N/A	GREEN	GREEN	GREEN
Ceiling jet temperature (“target/gas temperature”)		N/A	YELLOW+	YELLOW+	GREEN	GREEN
Plume temperature		YELLOW–	YELLOW+	N/A	GREEN	YELLOW
Flame height		GREEN	GREEN	GREEN	GREEN	YELLOW
Oxygen concentration		N/A	N/A	GREEN	YELLOW	GREEN
Smoke concentration		N/A	N/A	YELLOW	YELLOW	YELLOW
Room pressure		N/A	N/A	GREEN	GREEN	GREEN
Target temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Radiant heat flux		YELLOW	YELLOW	YELLOW	YELLOW	YELLOW
Total heat flux		N/A	N/A	YELLOW	YELLOW	YELLOW
Wall temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Total heat flux to walls		N/A	N/A	YELLOW	YELLOW	YELLOW

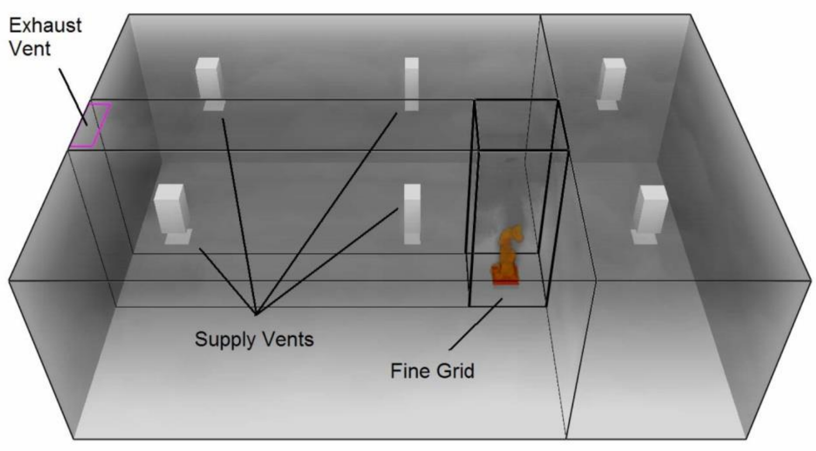
Uncertainty analysis

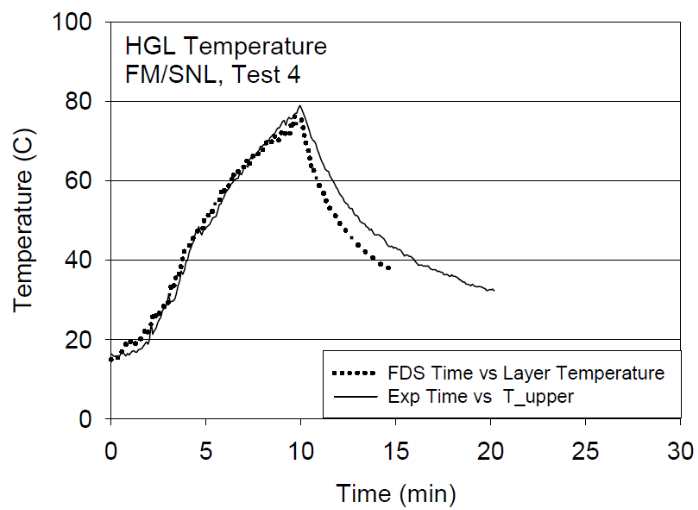
- Parameter Uncertainty – refers to the contribution of the uncertainty in the input parameters to the total uncertainty of the simulation

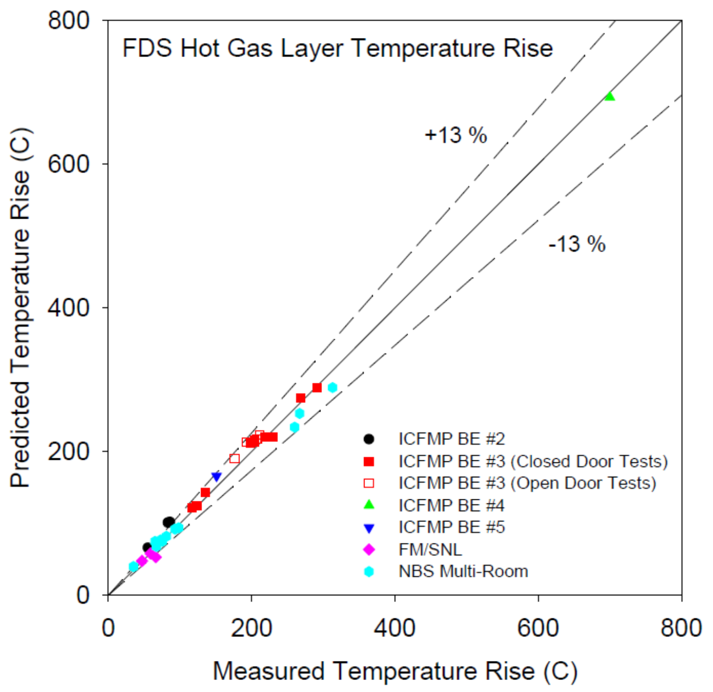
- Model Uncertainty – refers to the effect of the model assumptions, simplified physics, numerics, etc.

- Completeness Uncertainty – refers to physics that are left out of the model. For most, this is a form of Model Uncertainty.

Fire Model Validation Study, NUREG-1824







Results of NUREG-1824

Table 4-1. Results of the V&V study, NUREG-1824 (EPRI 1011999).

Output Quantity	FDTs		FIVE		CFAST		MAGIC		FDS		Exp
	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	$\tilde{\sigma}_E$
HGL Temperature Rise*	1.44	0.25	1.56	0.32	1.06	0.12	1.01	0.07	1.03	0.07	0.07
HGL Depth*	N/A		N/A		1.04	0.14	1.12	0.21	0.99	0.07	0.07
Ceiling Jet Temp. Rise	N/A		1.84	0.29	1.15	0.24	1.01	0.08	1.04	0.08	0.08
Plume Temperature Rise	0.73	0.24	0.94	0.49	1.25	0.28	1.01	0.07	1.15	0.11	0.07
Flame Height**	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.
Oxygen Concentration	N/A		N/A		0.91	0.15	0.90	0.18	1.08	0.14	0.05
Smoke Concentration	N/A		N/A		2.65	0.63	2.06	0.53	2.70	0.55	0.17
Room Pressure Rise	N/A		N/A		1.13	0.37	0.94	0.39	0.95	0.51	0.20
Target Temperature Rise	N/A		N/A		1.00	0.27	1.19	0.27	1.02	0.13	0.07
Radiant Heat Flux	2.02	0.59	1.42	0.55	1.32	0.54	1.07	0.36	1.10	0.17	0.10
Total Heat Flux	N/A		N/A		0.81	0.47	1.18	0.35	0.85	0.22	0.10
Wall Temperature Rise	N/A		N/A		1.25	0.48	1.38	0.45	1.13	0.20	0.07
Wall Heat Flux	N/A		N/A		1.05	0.43	1.09	0.34	1.04	0.21	0.10

NUREG-1824 Supplement (draft)

- The purpose of this supplement is to expand the evaluation of the predictive capabilities of certain fire models for applications specific to NPPs
  - Considers empirical correlations directly (e.g., MQH) instead of implementation (e.g., FDTs)
  - Expands on experimental database and on parameter range

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Table 3-2. Summary of major experiment parameters.

Experiment	Experiment Parameters									
	$\dot{Q}$ (kW)	D (m)	H (m)	$\dot{Q}^*$	L_f/H	φ	W/H	L/H	r_{cj}/H	r/D
ATF Corridors	50-500	0.5	2.4	0.3-3.3	0.3-0.9	0.0-0.1	0.8	7.1	0.8-6.0	N/A
Fleury	100-300	0.3-0.6	Open	0.3-5.5	Open	Open	Open	Open	Open	0.8-8
FM/SNL	470-2000	0.9	6.1	0.6-2.4	0.3-0.6	0.0-0.2	2.0	3.0	0.2-0.3	N/A
LLNL	50-400	0.6	4.5	0.2-1.5	0.1-0.4	0.1-0.4	0.9	1.3	0.3-1.0	N/A
NBS Multi-Room	110	0.3	2.4	1.5	0.5	0.0	1.0	5.1	N/A	N/A
NIST/NRC	350-2200	1.0	3.8	0.3-2.0	0.3-1.0	0.0-0.3	1.9	5.7	0.3-2.1	2-4
SP AST	450	0.3	2.4	6.1	0.9	0.1	1.0	1.5	N/A	N/A

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Steckler	32-158	0.3	2.1	0.8-3.8	0.3-0.7	0.0-0.5	1.3	1.3	N/A	N/A
UL/NFPRF	4400-10000	1.0	7.6	4.0-9.1	0.7-1.0	NA	4.9	4.9	0.6-3.9	N/A
UL/NIST Vents	500-2000	0.9	2.4	0.7-2.6	0.8-1.6	0.2-0.6	1.8	2.5	1.0-2.3	N/A
USN Hawaii	100-7700	0.3-2.5	15	0.7-1.3	0.1-0.4	NA	4.9	6.5	0-1.2	N/A
USN Iceland	100-15700	0.3-3.4	22	0.7-1.3	0.0-0.3	NA	2.1	3.4	0-1.0	N/A
Vettori Flat	1055	0.7	2.6	2.5	1.1	0.3	2.1	3.5	0.8-2.9	N/A
Vettori Sloped	1055	0.7	2.5	2.5	1.2	0.3	2.2	2.9	N/A	N/A
VTT Hall	1860-3640	1.2-1.6	19	1.0-1.1	0.2	0-0.09	1.0	1.4	0-0.6	N/A
WTC	1970-3240	1.6	3.8	0.6-0.9	0.8-1.1	0.3-0.5	0.9	1.8	0-0.8	0.3-1.3

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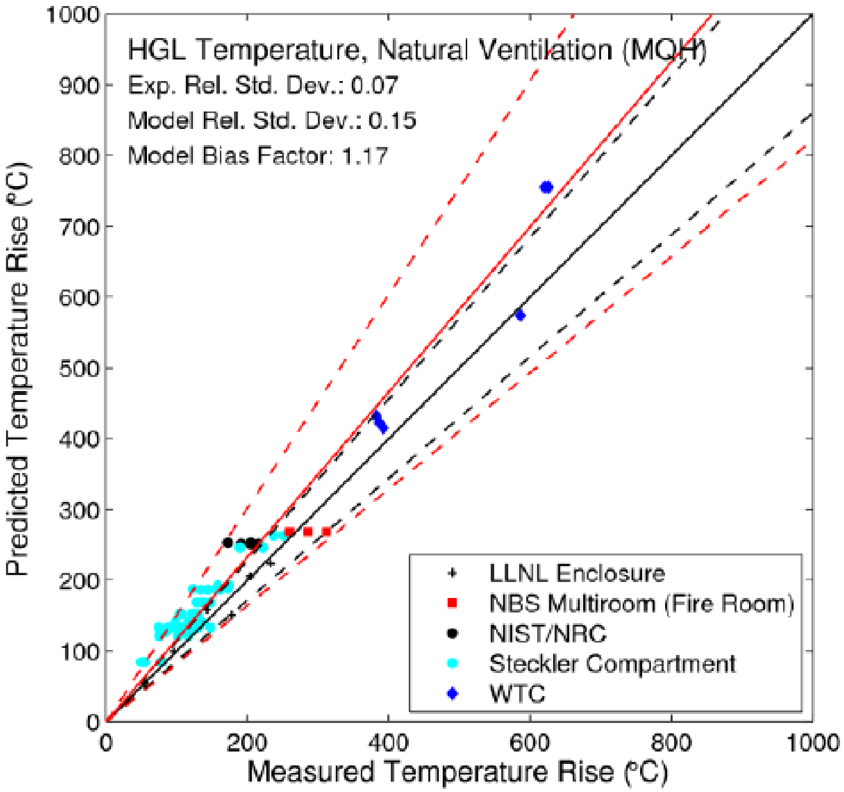

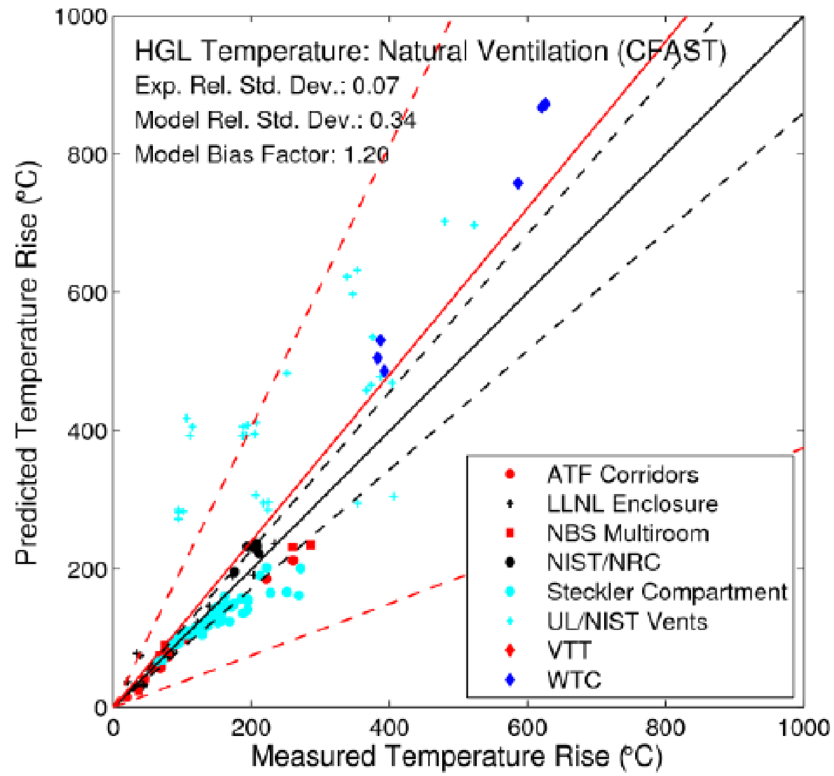

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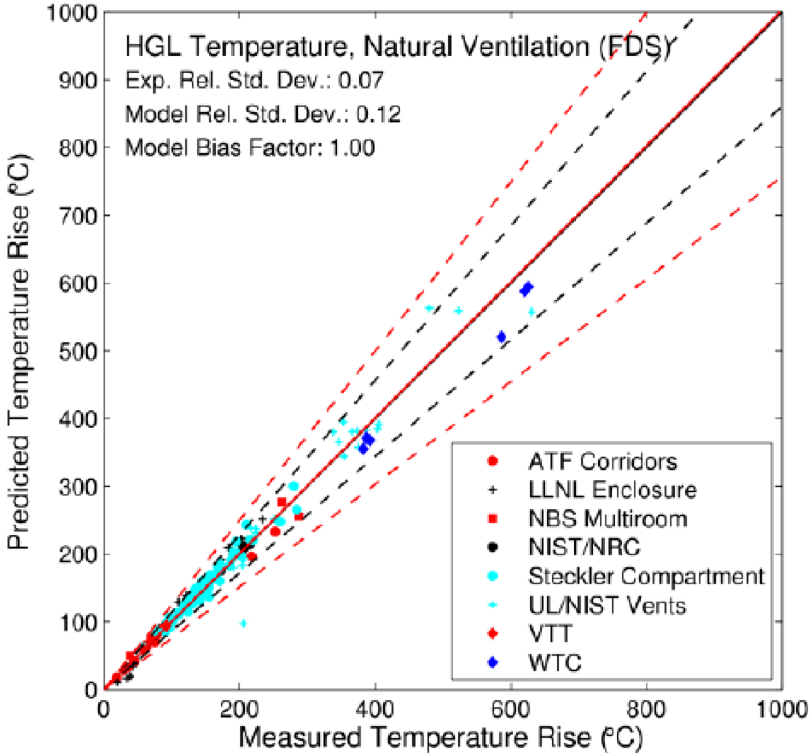

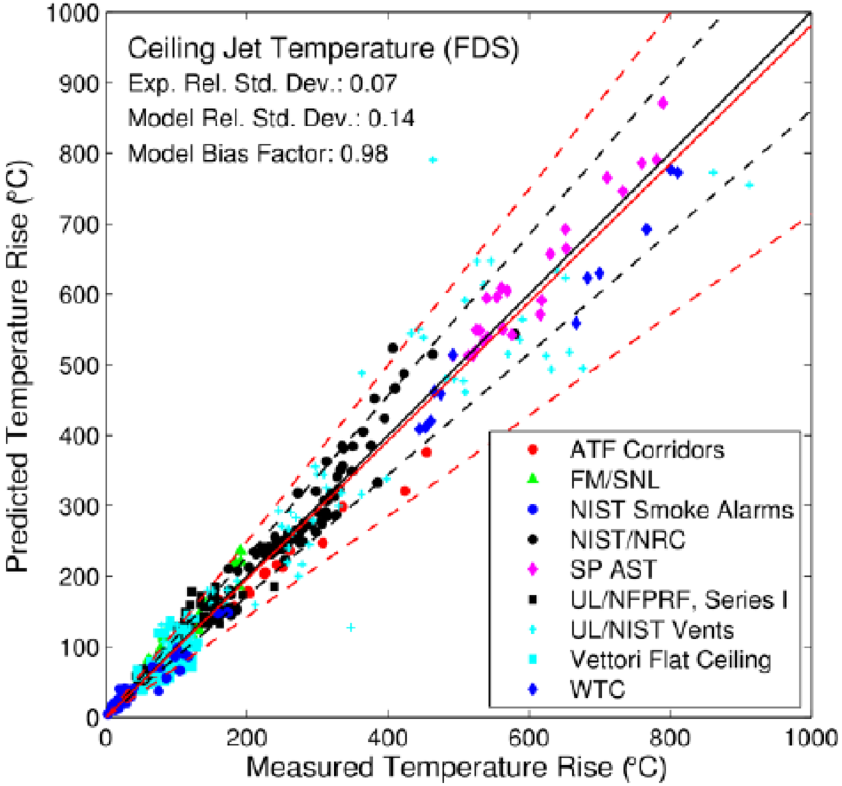

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Table 5-1. Summary of model uncertainty metrics.

Output Quantity	Empirical Correlations			CFAST		MAGIC		FDS		Exp
	Corr.	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	$\tilde{\sigma}_E$
HGL Temp. Rise, Natural	MQH	1.17	0.15	1.20	0.34	1.13	0.30	1.00	0.12	0.07
HGL Temp. Rise, Forced	FPA	1.29	0.32	1.15	0.20	1.08	0.17	1.21	0.22	0.07
	DB	1.18	0.25							
HGL Temp. Rise, Closed	Beyler	1.04	0.37	0.99	0.08	1.07	0.16	1.20	0.12	0.07
HGL Depth	ASET/YT	-	-	1.12	0.36	1.17	0.31	1.03	0.06	0.05
Ceiling Jet Temp. Rise	Alpert	0.86	0.11	1.18	0.33	1.04	0.45	0.98	0.14	0.07
Plume Temp. Rise	Heskestad	0.84	0.33	1.08	0.20	1.04	0.20	1.20	0.21	0.07
	McCaffrey	0.90	0.31							
Oxygen Concentration	N/A			1.00	0.15	0.93	0.22	1.01	0.11	0.08
Smoke Concentration	N/A			3.16	0.68	3.71	0.66	2.63	0.59	0.19

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Pressure Rise	N/A			1.36	0.66	1.49	0.45	0.96	0.27	0.21
Target Temp. Rise	Steel	1.29	0.45	1.58	0.64	1.08	0.38	0.98	0.18	0.07
Target Heat Flux	Point Source	1.44	0.47	0.93	1.16	0.85	0.66	0.98	0.25	0.11
	Solid Flame	1.17	0.44							
Surface Temp. Rise	N/A			1.05	0.28	0.95	0.29	0.99	0.12	0.07
Surface Heat Flux	N/A			0.98	0.34	0.78	0.35	0.92	0.15	0.11
Cable Failure Time	THIEF	0.90	0.11	-	-	-	-	1.10	0.16	0.12
Sprinkler Activation Time	Sprinkler	1.11	0.41	0.80	0.21	0.91	0.20	0.93	0.15	0.06
Smoke Detector Act. Time	Temp. Rise	0.66	0.57	1.12	0.46	1.54	0.36	0.85	0.29	0.34

Procedure for Calculating Model Uncertainty

1. Express the predicted value in terms of a rise above ambient. For example, subtract the ambient temperature from the predicted temperature. Call this value M.
2. Find the values of model bias and relative standard deviation from table on previous slide. Compute the mean and standard deviation of normal distribution:

$$\mu = M/\delta \qquad\qquad \sigma = \tilde{\sigma}_M (M/\delta)$$

Compute the probability of exceeding the critical value:

$$P(x > x_c) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{x_c - \mu}{\sigma\sqrt{2}}\right)$$

4.3.1 Example 1: Target Temperature

Suppose that cables within a compartment are assumed to fail if their surface temperature reaches 330 °C (625 °F). The model FDS predicts that the maximum cable temperature due to a fire in an electrical cabinet is 300 °C (570 °F). What is the probability that the cables could fail?

Step 1: Subtract the ambient value of the cable temperature, 20 °C (68 °F) to determine the predicted temperature *rise*. Refer to this value as the *model prediction*:

$$M = 300 - 20 = 280°\mathrm{C} \tag{4-6}$$

Step 2: Refer to Table 4-1, which indicates that, on average, FDS overpredicts Target Temperatures with a bias factor, δ, of 1.02. Calculate the *adjusted model prediction*:

$$\mu = \frac{M}{\delta} = \frac{280}{1.02} = 275°\mathrm{C} \tag{4-7}$$

Referring again to Table 4-1, calculate the standard deviation of the distribution:

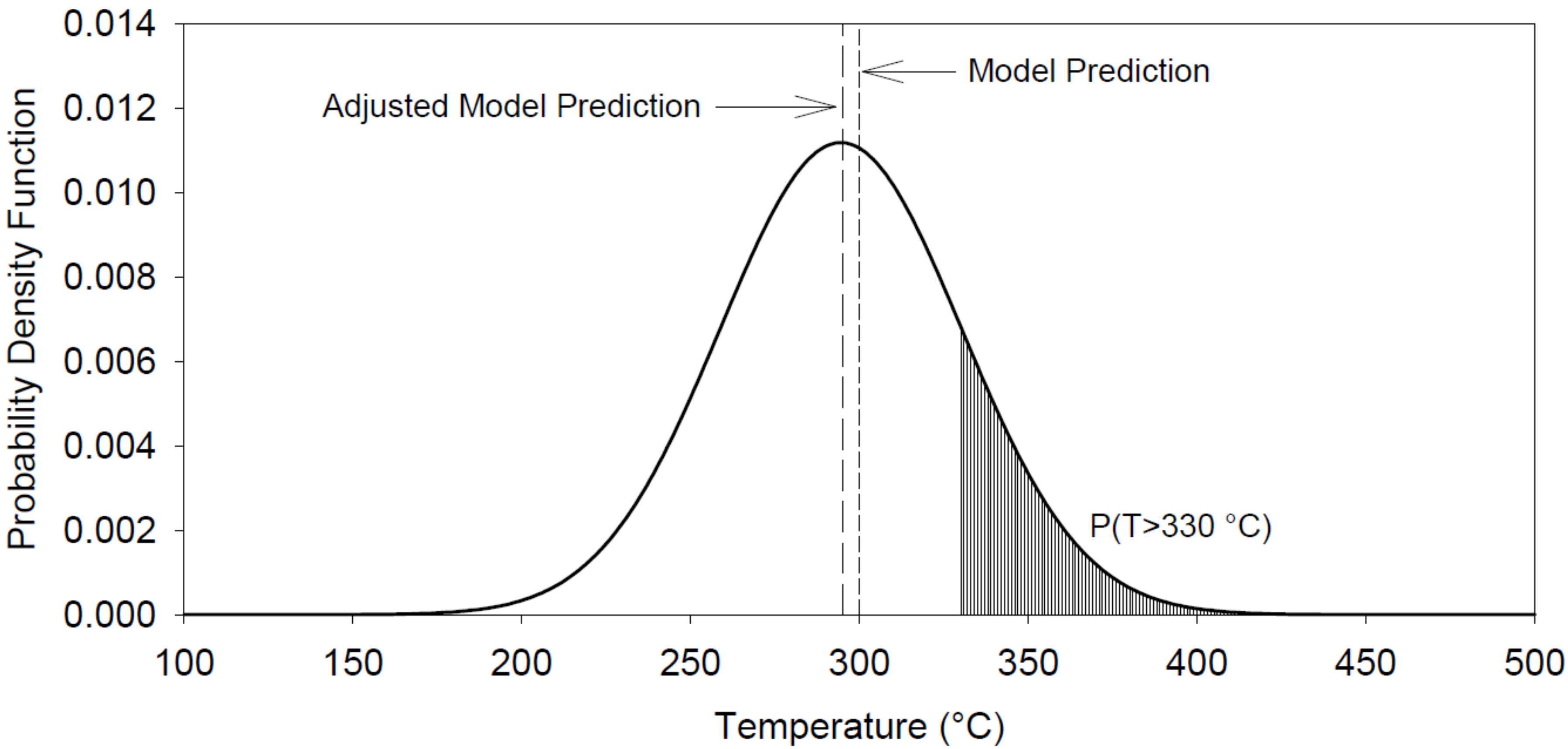
$$\sigma = \tilde{\sigma}_M \left(\frac{M}{\delta}\right) = 0.13 \left(\frac{280}{1.02}\right) = 36°\mathrm{C} \tag{4-8}$$

Step 3: Calculate the probability that the actual cable temperature would exceed 330°C:

$$P(T > 330) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{T - T_0 - \mu}{\sigma\sqrt{2}}\right) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{330 - 20 - 275}{36\sqrt{2}}\right) = 0.16 \tag{4-9}$$

The process is shown graphically in Figure 4-3. The area under the “bell curve” for temperatures higher than 330 °C (625 °F) represents the probability that the actual cable temperature would exceed that value. Note that this estimate is based only on the model uncertainty.

Example 1



Model Prediction
Adjusted Model Prediction
P(T>330 °C)
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Probability Density Function
100
150
200
250
300
350
400
450
500
Temperature (°C)

4.3.2 Example 2: Critical Heat Flux

As part of a screening analysis, the model MAGIC is used to predict the radiant heat flux from a fire to a nearby group of thermoplastic cables. According to NUREG/CR-6850 (EPRI 1011989), Appendix H, one of the damage criteria for thermoplastic cables is a radiant heat flux to the target cable that exceeds 6 kW/m^2. The model, by coincidence, predicts a heat flux of 6 kW/m^2. What is the probability that the actual heat flux from a fire will be 6 kW/m^2 or greater? Assume for this exercise that the model input parameters are not subject to uncertainty, only the model itself.

Step 1: Unlike in the previous example, there is no need to subtract an ambient value of the heat flux (it is zero). Thus, the *model prediction* is:

$$M = 6 \text{ kW/m}^2 \qquad (4\text{-}10)$$

Step 2: Refer to Table 4-1, which indicates that, on average, MAGIC overpredicts Radiant Heat Flux with a bias factor, δ, of 1.15. Calculate the *adjusted model prediction*:

$$\mu = \frac{M}{\delta} = \frac{6}{1.15} \approx 5.2 \text{ kW/m}^2 \qquad (4\text{-}11)$$

Referring again to Table 4-1, calculate the standard deviation of the distribution:

$$\sigma = \tilde{\sigma}_M \left(\frac{M}{\delta}\right) = 0.36 \left(\frac{6}{1.15}\right) \approx 1.9 \text{ kW/m}^2 \qquad (4\text{-}12)$$

Step 3: Calculate the probability that the actual heat flux, $\dot{q}''$, will exceed the critical value of the heat flux, $\dot{q}_c'' = 6$ kW/m^2:

$$P(\dot{q}'' > 6) = \frac{1}{2} \operatorname{erfc}\left(\frac{\dot{q}_c'' - \mu}{\sigma\sqrt{2}}\right) = \frac{1}{2} \operatorname{erfc}\left(\frac{6 - 5.2}{1.9\sqrt{2}}\right) \approx 0.34 \qquad (4\text{-}13)$$

This is a somewhat surprising result. Even though the model predicts a peak radiant heat flux equal to the critical value, there is only a one in three chance that the actual heat flux would exceed this value. This is mainly due to the fact that MAGIC has been shown to over-predict the heat flux by about 15%.

Sensitivity Analysis to Address Parameter Uncertainty

Output Quantity = Constant × (Input Parameter)$^{\text{Power}}$

Example: MQH correlation states that the HGL temperature rise is proportional to the HRR to the 2/3 power:

$$T - T_0 = C\dot{Q}^{2/3}$$

$$\frac{\Delta T}{T - T_0} \approx \frac{2}{3}\frac{\Delta\dot{Q}}{\dot{Q}}$$

Table 4-3. Sensitivity of model outputs from Volume 2 of NUREG-1824 (EPRI 1011999).

Output Quantity	Important Input Parameters	Power Dependence
HGL Temperature	HRR Surface Area Wall Conductivity Ventilation Rate Door Height	2/3 -1/3 -1/3 -1/3 -1/6
HGL Depth	Door Height	1
Gas Concentration	HRR Production Rate	1/2 1
Smoke Concentration	HRR Soot Yield	1 1
Pressure	HRR Leakage Rate Ventilation Rate	2 2 2
Heat Flux	HRR	4/3
Surface/Target Temperature	HRR	2/3

Sensitivity example

- Suppose, for example, that as part of an NFPA 805 analysis the problem is to determine the Limiting Fire Scenario for a particular compartment whose HGL temperature is not to exceed 500 °C (930 °F). Assume that the geometrical complexity of the compartment rules out the use of the empirical and zone models, and that FDS has been selected for the simulation.

  Step 1: Determine an appropriate maximum expected fire heat release rate. For this example, suppose that a 98th percentile HRR for the electrical cabinet fire, 702 kW, has been determined to be the MEFS. Choose a model and calculate the peak HGL temperature.

  Step 2: Assume that FDS predicts 450 °C (840 °F) for the selected fire scenario. Adjust the prediction to account for the model bias, δ (See Table 4-1):

$$T_{\text{adj}} = T_0 + \frac{T - T_0}{\delta} = 20 + \frac{450 - 20}{1.03} \approx 437°\text{C} \qquad (4\text{-}17)$$

  Step 3: Calculate the change in HRR required to increase the HGL temperature to 500 °C (930 °F):

$$\Delta\dot{Q} \approx \frac{3}{2}\dot{Q}\frac{\Delta T}{T_{\text{adj}} - T_0} = \frac{3}{2}702\frac{500 - 437}{417} = 159\ \text{kW} \qquad (4\text{-}18)$$

  This calculation suggests that adding an additional 159 kW to the original 702 kW will produce an HGL temperature in the vicinity of 500 °C (930 °F). This result can be double-checked by re-running the model with the modified input parameters.

Propagating uncertainty

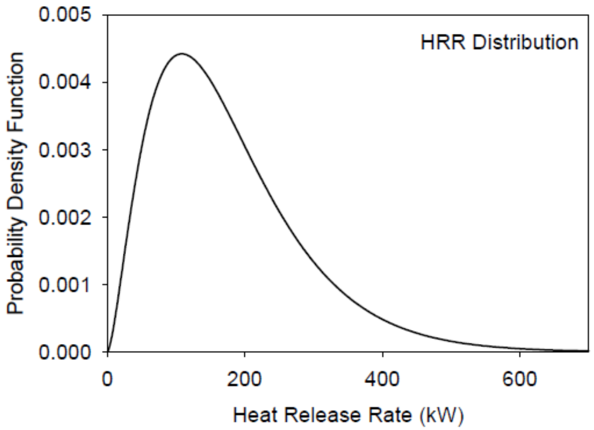
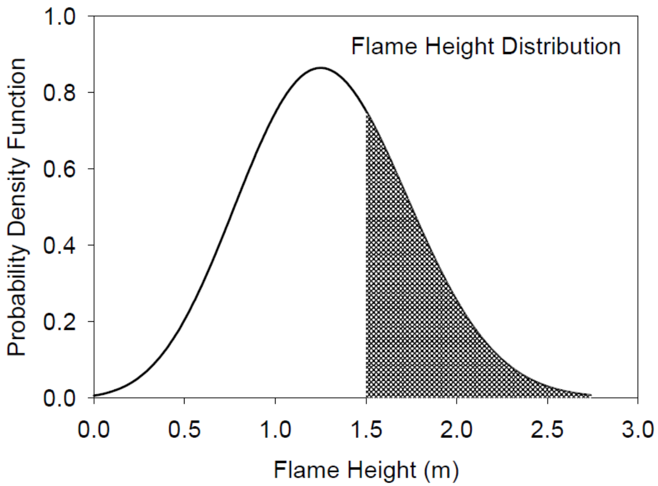


Figure 4-4. Distribution of HRR for an electrical cabinet fire.

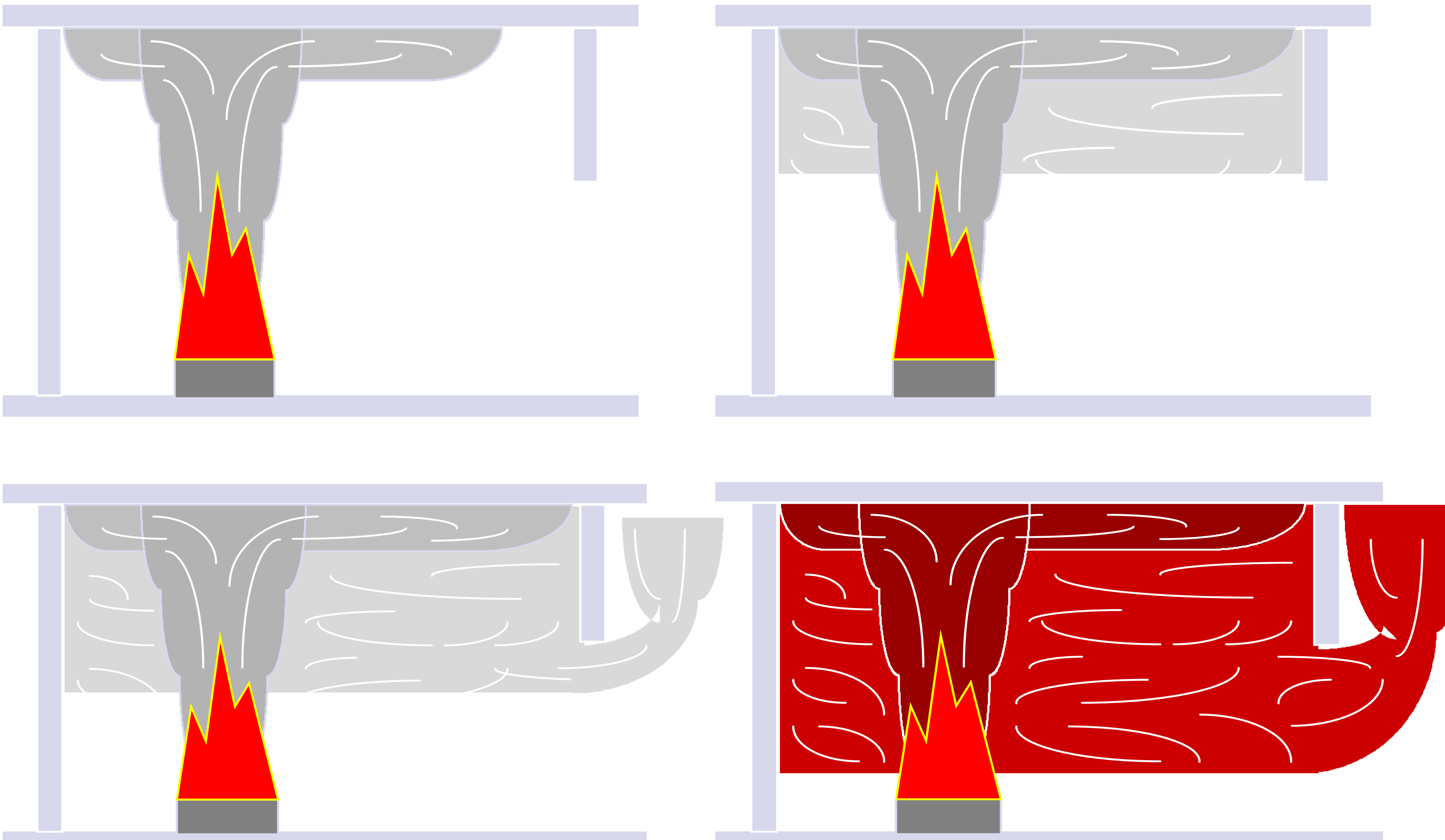
$$L_f = 0.235\,\dot{Q}^{2/5} - 1.02\,D$$



Fire modeling topics

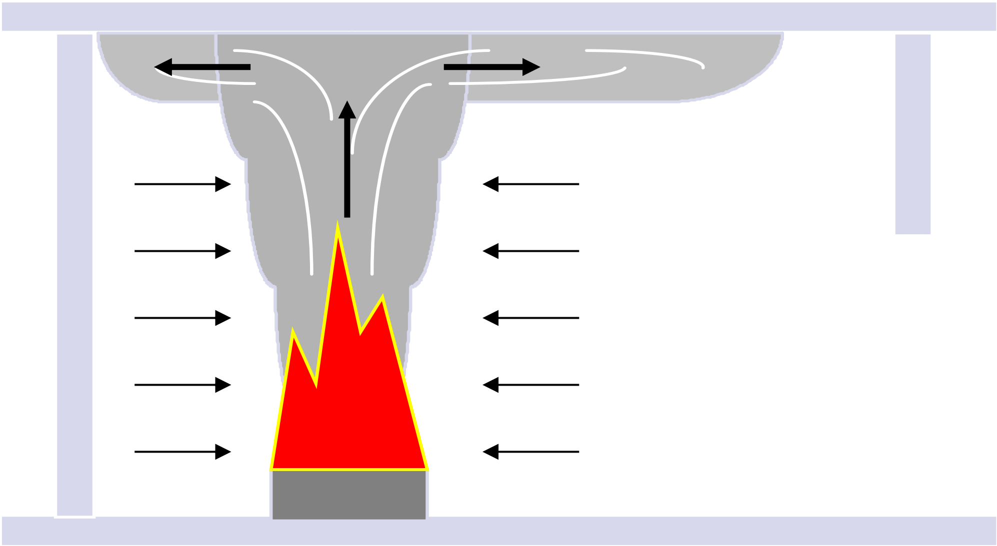
- Stages / elements of enclosure fires
- Fire source
- Fire plumes and ceiling jets
  - Smoke and heat detection
- Heat and smoke detection
- Enclosure smoke filling
- Pre- and post-flashover vented fires
  - Vent flows

Stages of enclosure fires



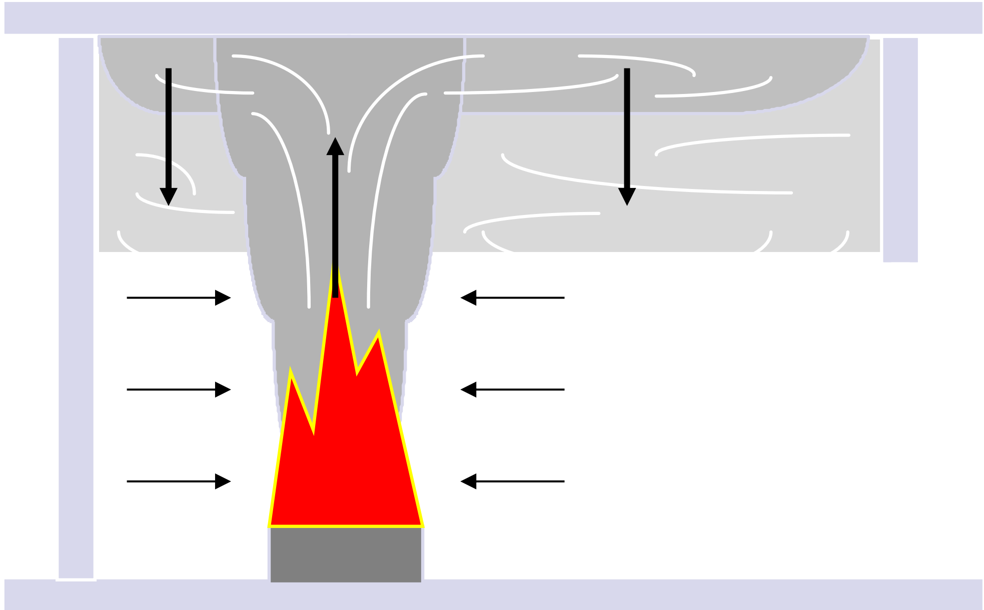
Stage 1 - Fire plume / ceiling jet period

- Buoyant gases rise to ceiling in fire plume
- Ceiling jet spreads radially until confined
- Plume entrains surrounding air
- Temperature decays rapidly with height and radial distance



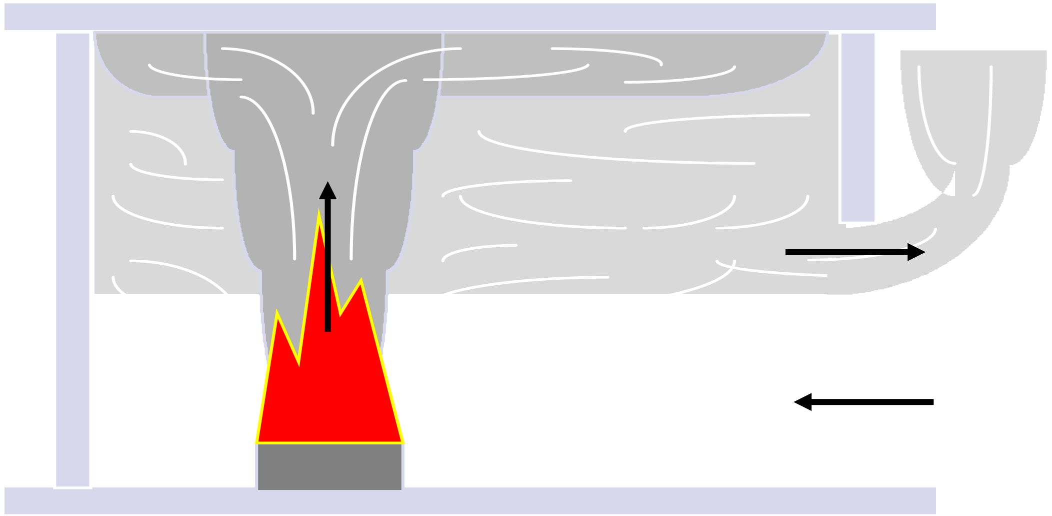
Stage 2 - Enclosure smoke filling period

- Period begins when ceiling jet reaches walls
- Period ends when smoke flows through vents
- Smoke layer fills due to entrainment / expansion



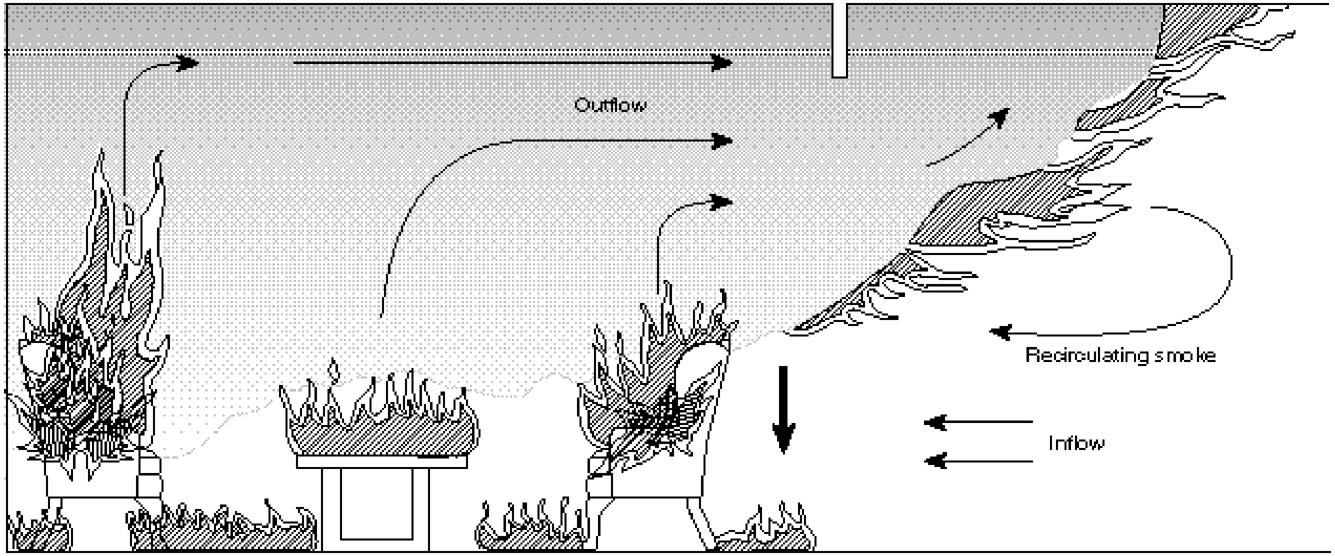
Stage 3 - Preflashover vented period

- Quasi-steady mass balance develops
- Smoke layer equilibrates at balance point
- Mass balance influenced by sizes, shapes and locations of vents and by mechanical ventilation
- Mass balance influences energy/species balances



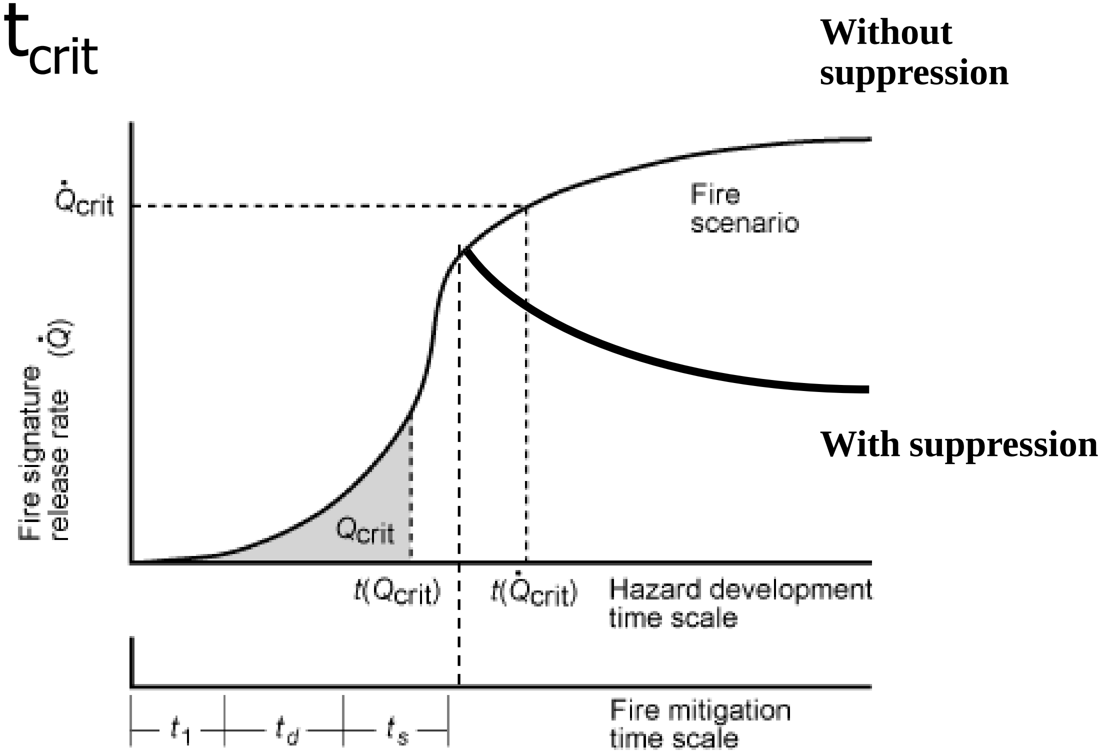
Stage 4 - Postflashover vented period

- Period begins when secondary fuels begin to ignite from radiant exposure
- Post-flashover fires frequently become ventilation-limited, with flames extending out of vents
- Underventilation affects smoke production



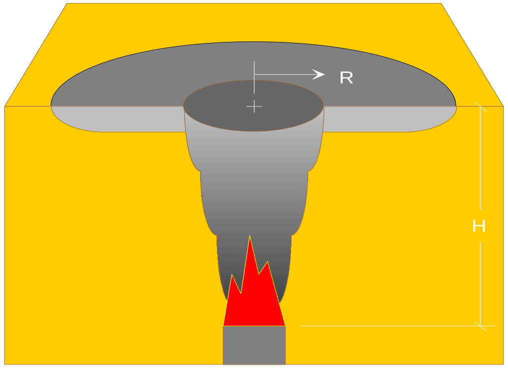
Fire scenario description

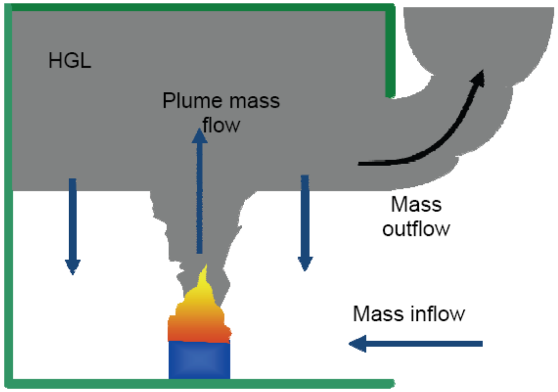
- Hazard development time scale
- Fire mitigation time scale
- Objective: $t_{mit} < t_{crit}$

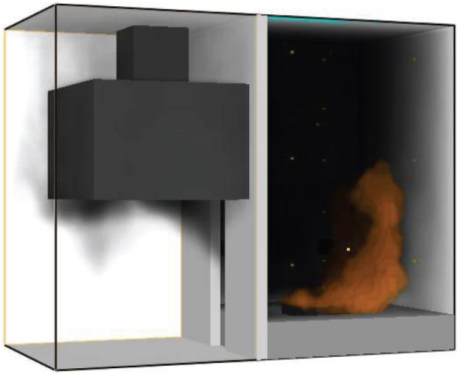


Types of fire models

- Empirical correlations
  - Algebraic equations
- Zone models
  - CFAST
- CFD models
  - FDS







Design fire

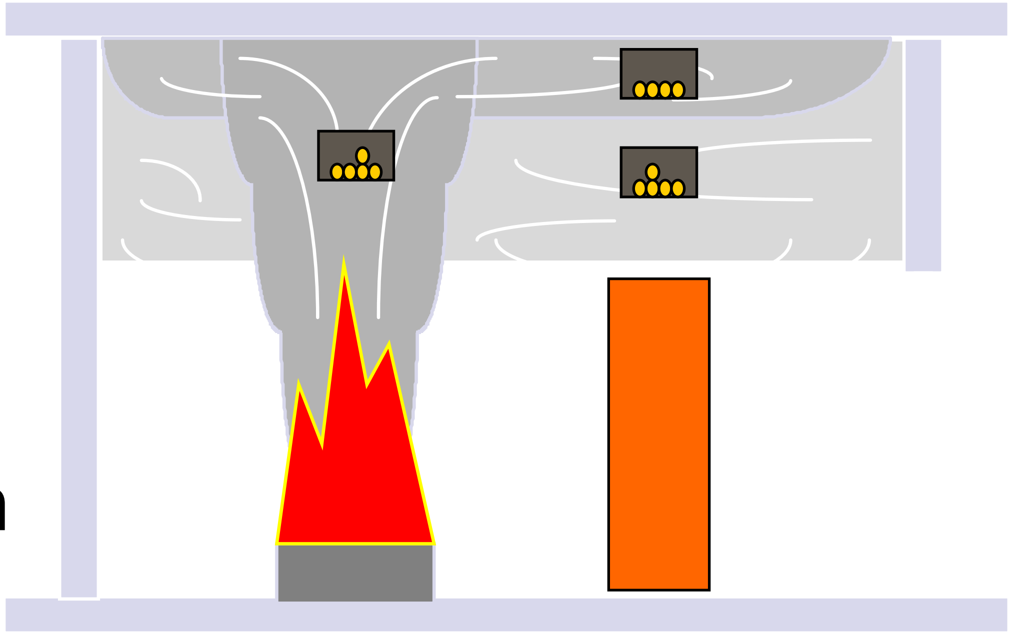
- HRR as f(t) is termed the *design fire*
- Approaches to determining *design fire*:
  - Knowledge of amount/type of combustibles
    - Object assumed to ignite and burn at known rate
    - Rate based on experimental data
  - Knowledge of occupancy
    - Little detailed data regarding specific fuels
    - Design fire based on statistics / eng. judgment

Design fire issues

- Target damage
  - Target vulnerability vs exposure conditions
- Structural stability
  - Fully developed post-flashover fire
  - Relatively long time frame (~1/2 -3 hours)
- Occupant escape / firefighting response
  - Developing fire
  - Relatively short time frame (<~1/2 hour)
- No exact methodology or procedure
  - Requires engineering judgment

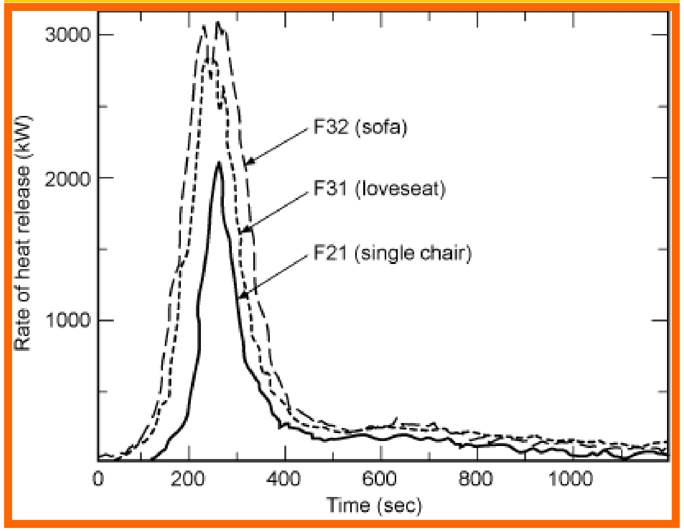
Elements of enclosure fires

- Fire source
- Fire plume
- Ceiling jet
- Upper gas layer
- Lower gas layer
- Vents / ventilation
- Boundaries
- Targets



The fire source

- First item
  - Ignition
  - Growth rate
  - Peak HRR
  - Burning duration
- Secondary items
  - Time to ignition
  - Burning histories



Heat release rate

$$\dot{Q} = \dot{m}'' A \Delta H_c$$

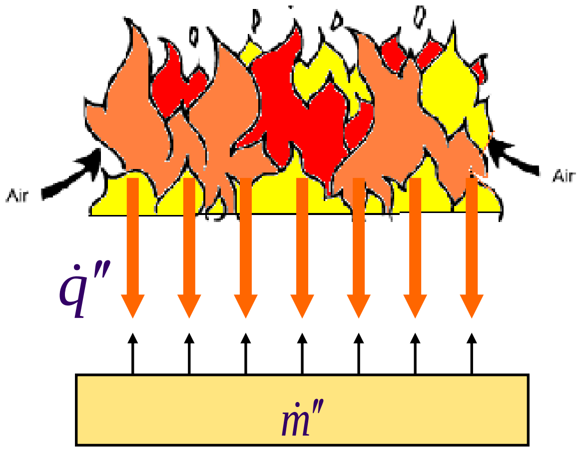
$\dot{m}''$ Mass loss rate per unit area

A Area of fuel that is burning

ΔH_c Fuel heat of combustion

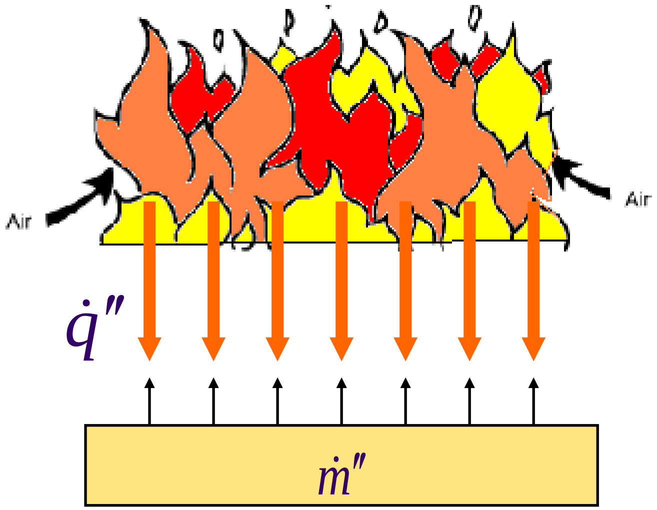
APPROX.HEATS OF COMBUSTION

FUEL	ΔH_c (kJ/g)
WOOD	15.0
POLYURETHANE	30.0
HEPTANE	44.5



Fuel burning rate

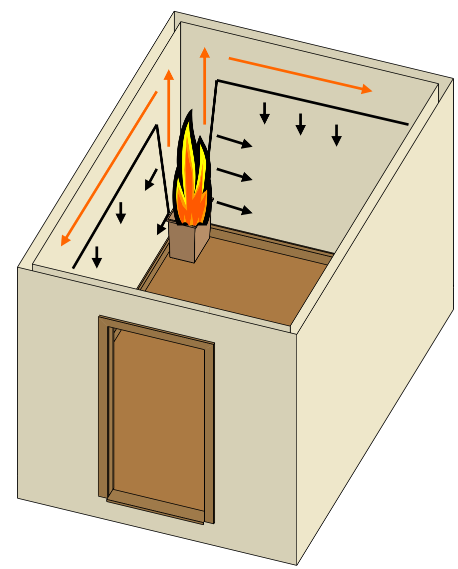
$$\dot{m}'' = \frac{\dot{q}''}{L}(\,g\,/\,m^2 s\,)$$



- LIQUIDS AT BOILING POINT
  - q″ Net heat flux to fuel surface
  - L Heat of gasification
- HEAT OF GASIFICATION, L
  - LIQUIDS: $L = \Delta h_{vap} + C_{liq}(T_b - T_o)$
    - (0.3 - 1.5 kJ/g typical)
  - SOLIDS: EFFECTIVE PROPERTY
    - (1 - 5 kJ/g typical)

Factors controlling HRRs

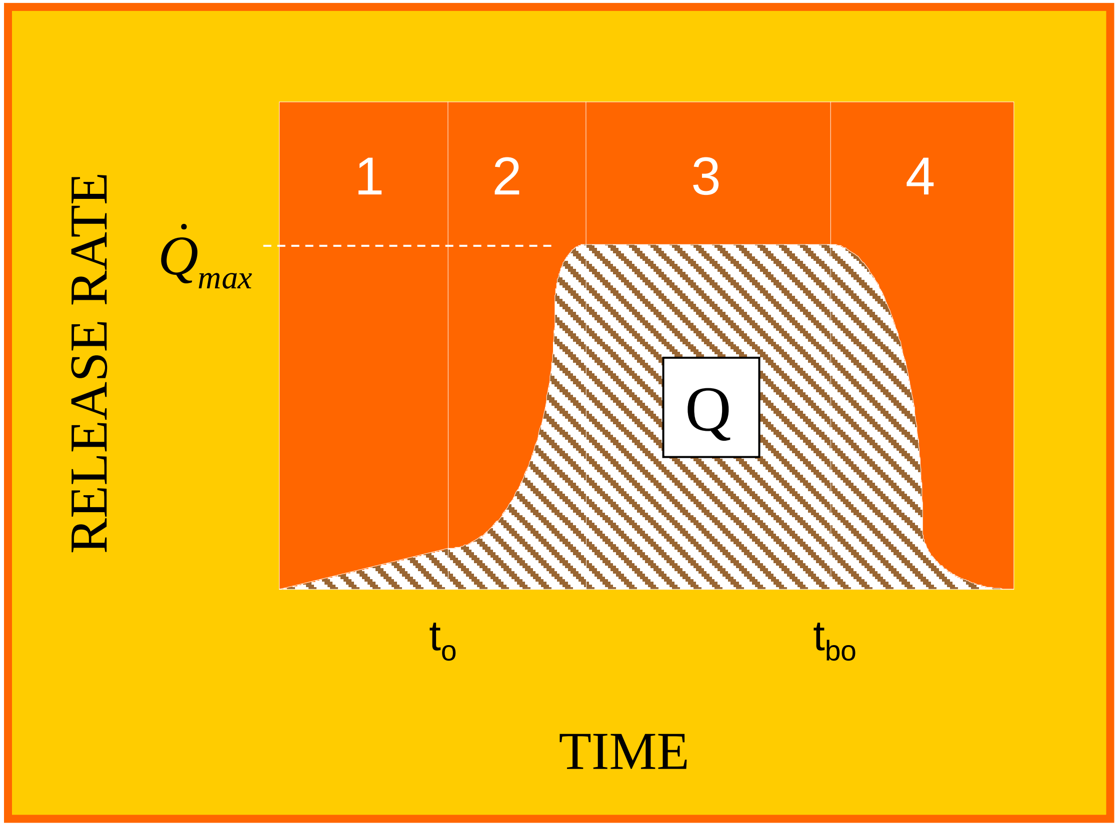
- Ignition scenarios
  - Ignition source magnitude
  - Ignition source duration
- Fuel characteristics
  - Type
  - Quantity
  - Orientation



- Enclosure effects
  - Radiation enhancement
  - Oxygen vitiation

Phases of fire development

- Incipient
- Growth
- Fully developed
- Decay / burnout



t^2 characterization

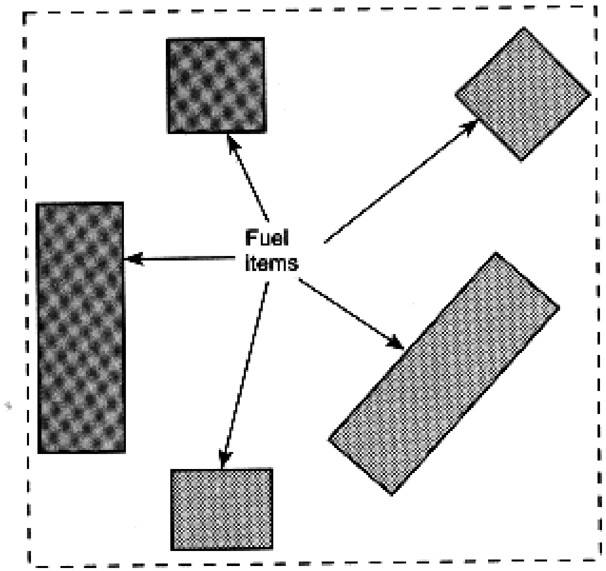
$$\dot{Q} = \dot{Q}_o \left(\frac{t}{t_g} \right)^2 ; \dot{Q}_o = 1055 (kW); \alpha = \frac{\dot{Q}_o}{t_g^{\ 2}}$$

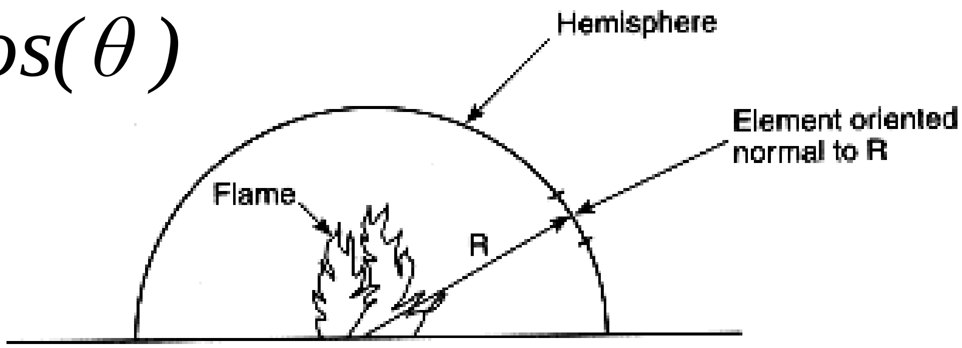
Growth rate	t_g (s)	α (kW/s^2)
Slow	600	0.003
Medium	300	0.012
Fast	150	0.047
Ultrafast	75	0.188

Secondary item ignition

- Factors
  - Heat flux from primary fire
  - Ease of ignition of target
- Point source estimate

$$\dot{q}_r'' = \frac{\chi_r \dot{Q}_f}{4\pi R^2 cos(\theta)}$$





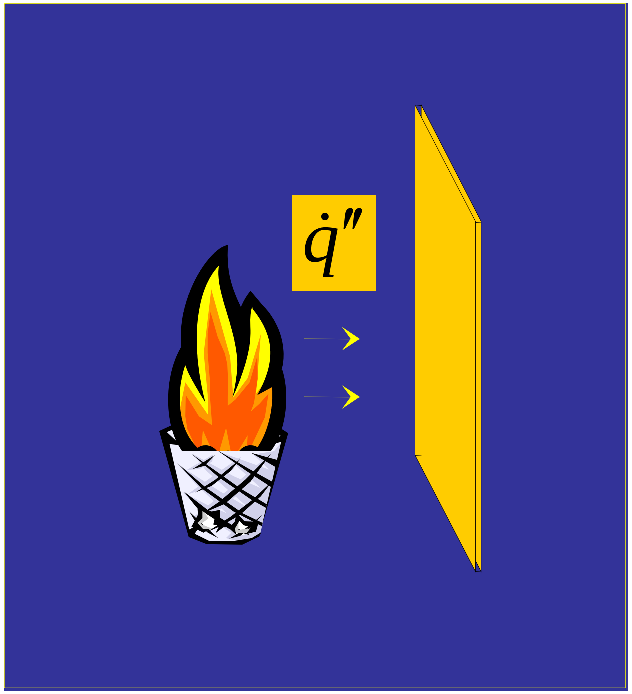
Secondary item ignition

- Ignition time estimates (constant heat flux)
  - Thermally thick materials

$$t_{ig} = \frac{\pi}{4} k\rho c \left[\frac{T_{ig} - T_o}{\dot{q}''} \right]^2$$

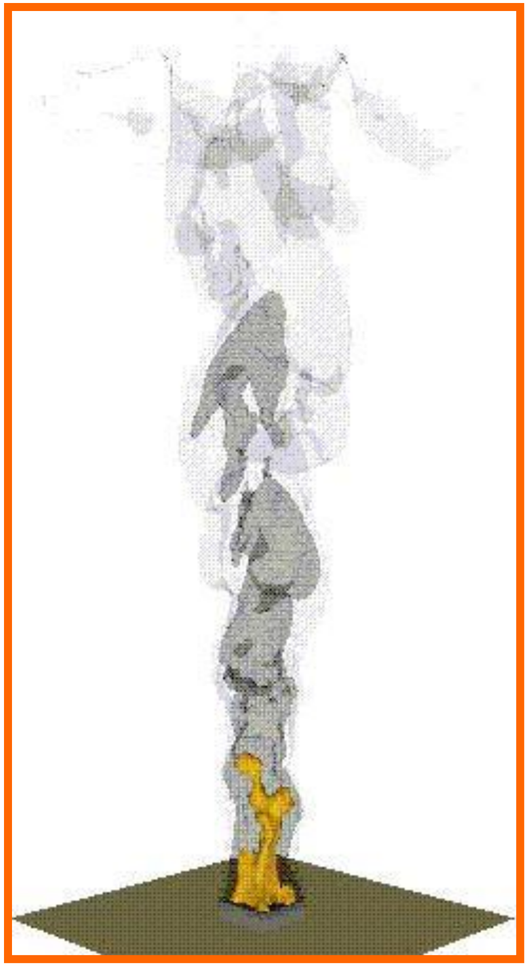
  - Thermally thin materials

$$t_{ig} = \frac{T_{ig} - T_o}{\dot{q}'' / \rho c \delta}$$



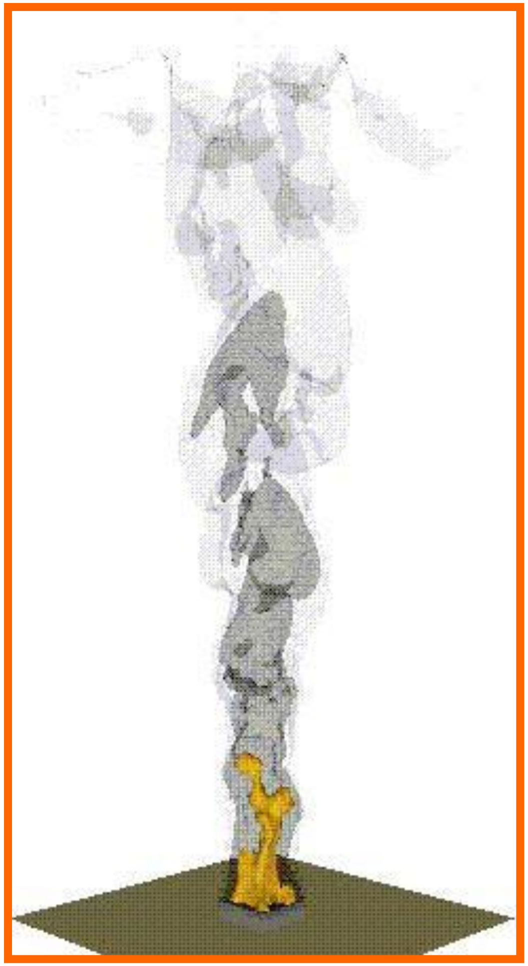
Fire plume issues

- Transports combustion products / entrained air vertically to ceiling
- Causes formation and descent of smoke layer
- Elevated temperatures and velocities expose targets located in plume



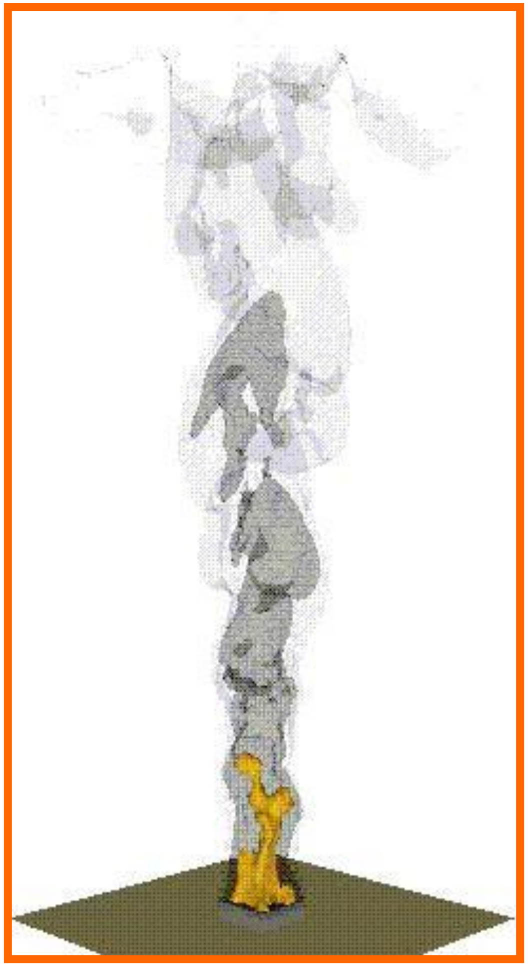
Fire plume topics

- Types of plumes
- Flame heights
- Flame/plume temperatures
- Entrainment in fire plumes
- Gas velocities in fire plumes



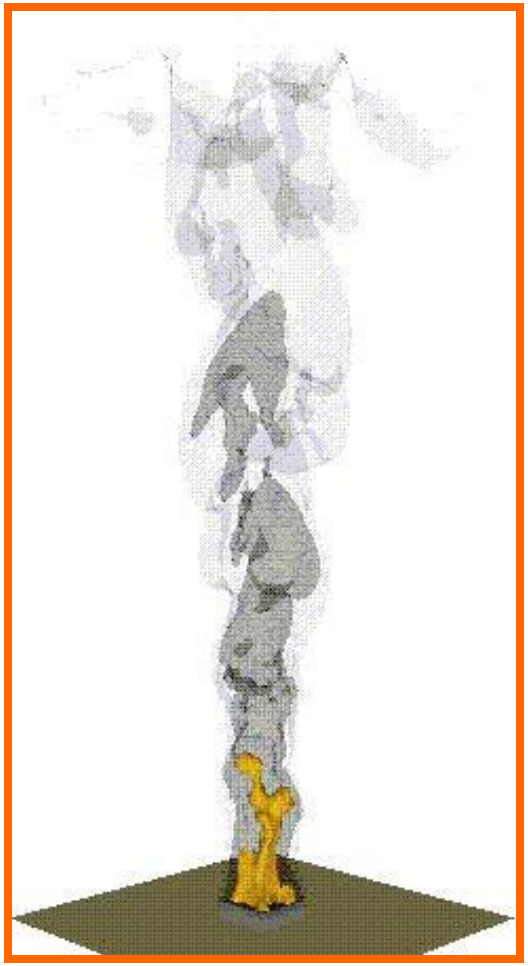
Types of fire plumes

- Axisymmetric plumes
- Line plumes
- Window plumes
- Balcony spill plumes
- Other …



Axisymmetric fire plumes

- Correlations
  - Morton-Taylor-Turner (ideal)
  - Zukoski
  - Heskestad
  - McCaffrey
  - Alpert
  - Alpert & Ward
  - Thomas

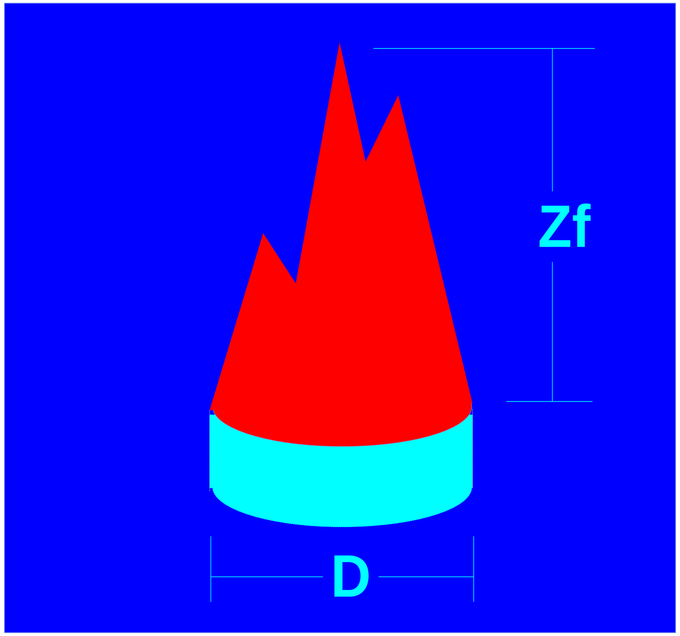


Flame height correlation

- Heskestad correlation

$$Z_f = 0.23\dot{Q}^{2/5} - 1.02D$$

$$\frac{Z_f}{D} = 3.7Q^{*2/5} - 1.02$$



The Heskestad plume

- Plume centerline temperature

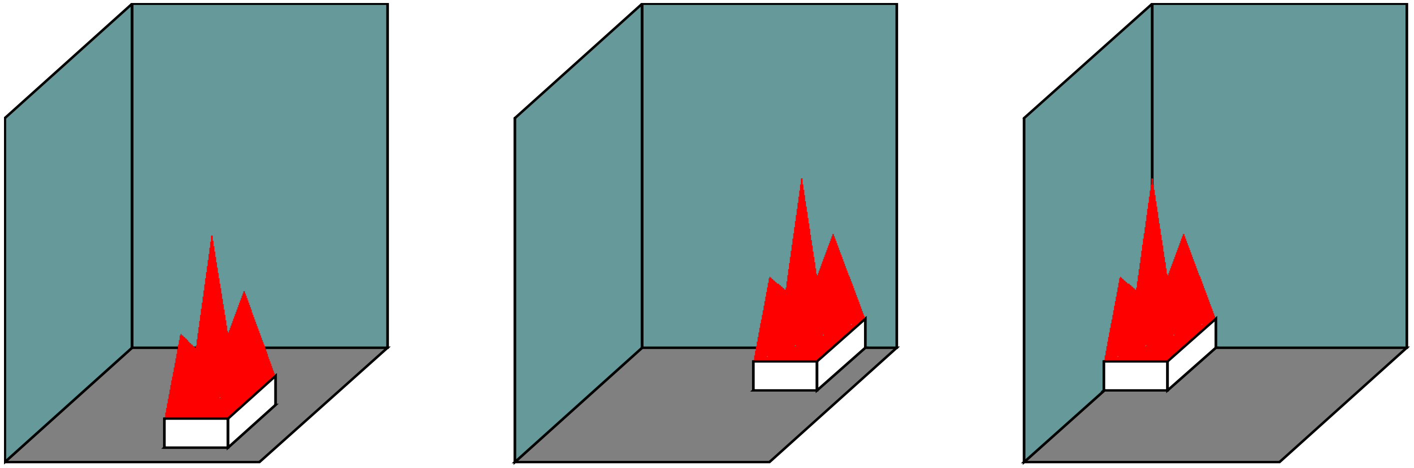
$$\Delta T_o \approx 25 \frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}}$$

- Plume centerline velocity

$$u_o = 3.4 \left(\frac{\dot{Q}_c \cdot g}{\rho_\infty c_p T_\infty} \right)^{1/3} \cdot (z - z_o)^{-1/3} = 1.03 \left(\frac{\dot{Q}_c}{z - z_o} \right)^{1/3}$$

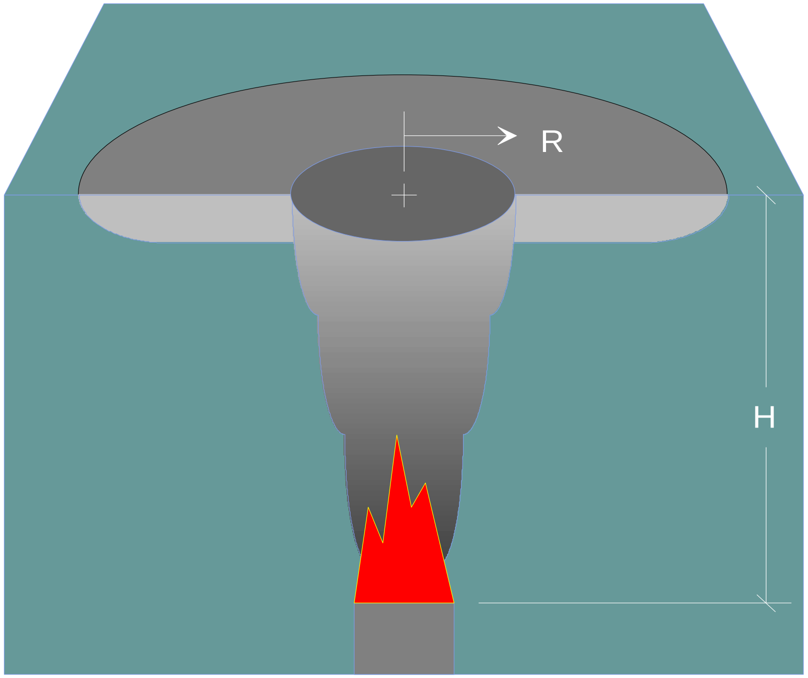
Fire location factors

- Multiply HRR by fire location factor
  - Fires in the open: $k_{lf} = 1$
  - Fires along walls: $k_{lf} = 2$
  - Fires in corners: $k_{lf} = 4$



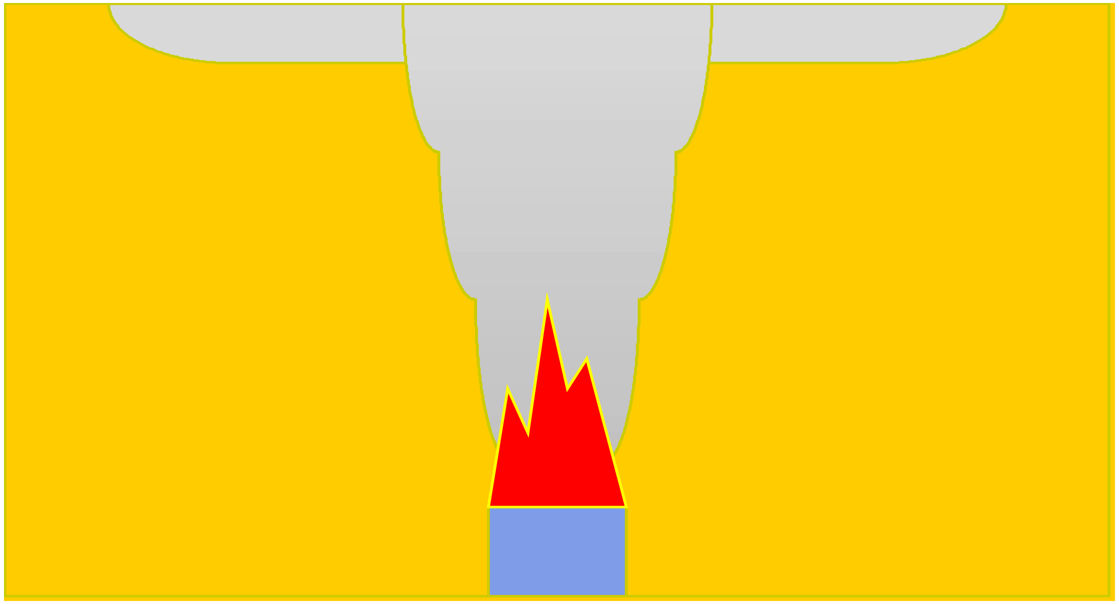
The ceiling jet

- Features
  - Relatively thin layer beneath ceiling (~0.1H)
  - Temperature, velocity decay as f(r)
- Analysis issues
  - Patterns
  - Target damage
  - Fire detector operation

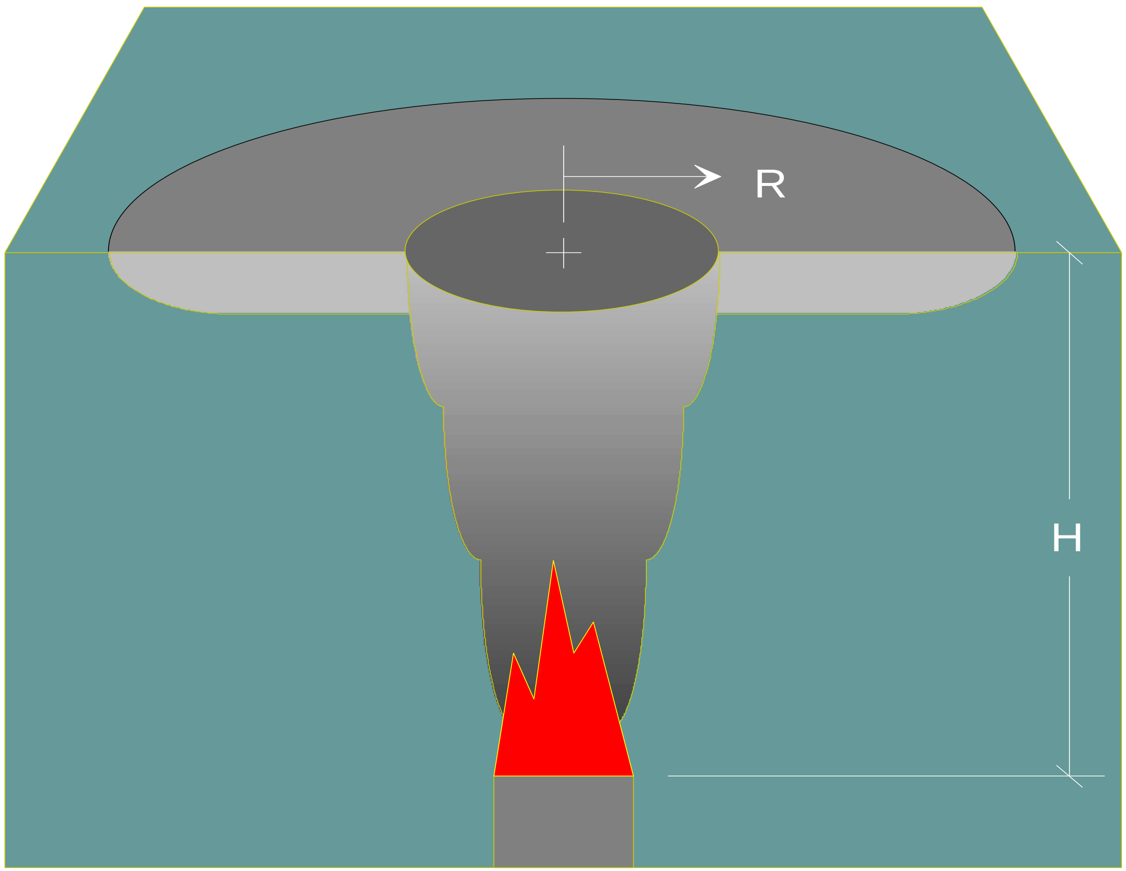


Ceiling jet topics

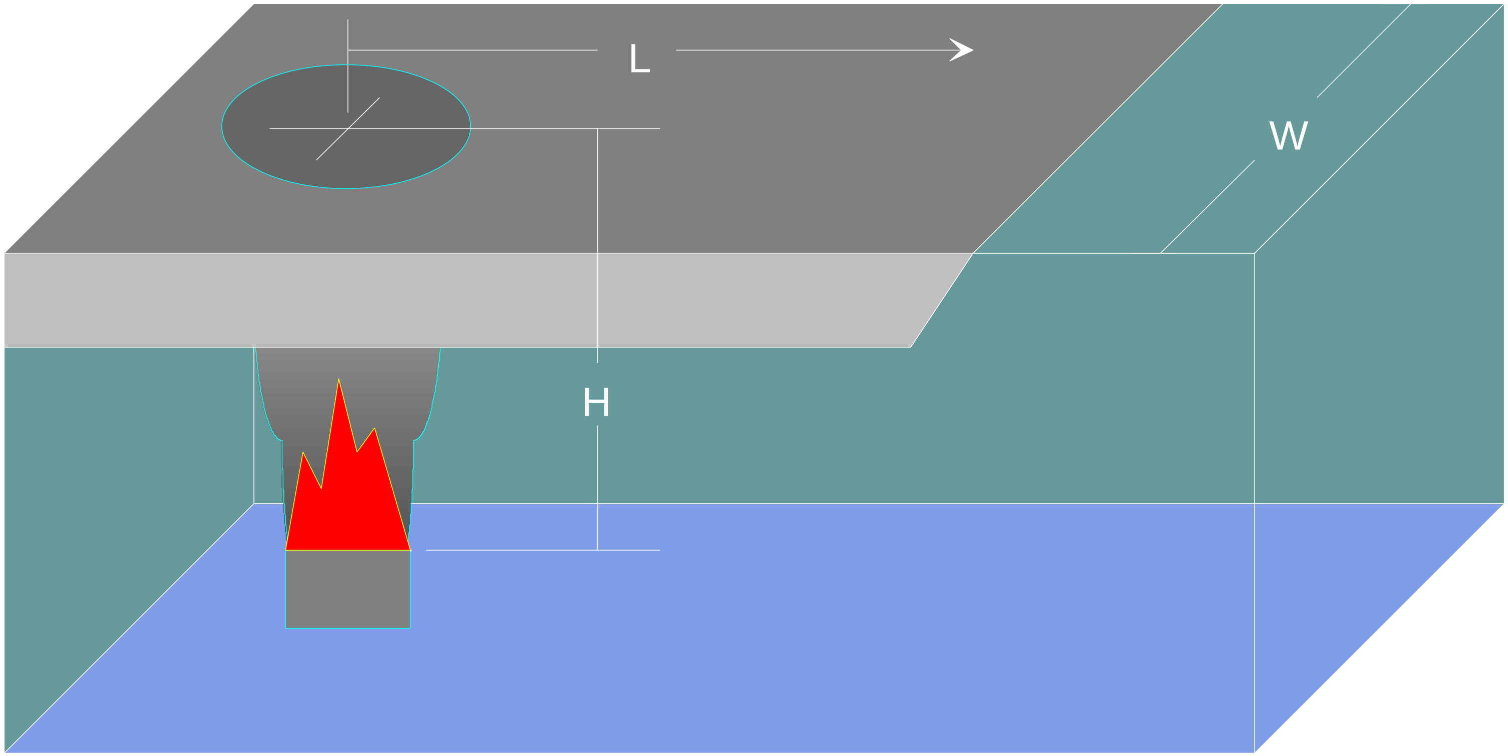
- Unconfined ceiling jets
- Confined ceiling jets
- Ceiling jet correlations
  - Temperature
  - Velocity



Unconfined ceiling jets



Confined ceiling jets



Unconfined ceiling jet

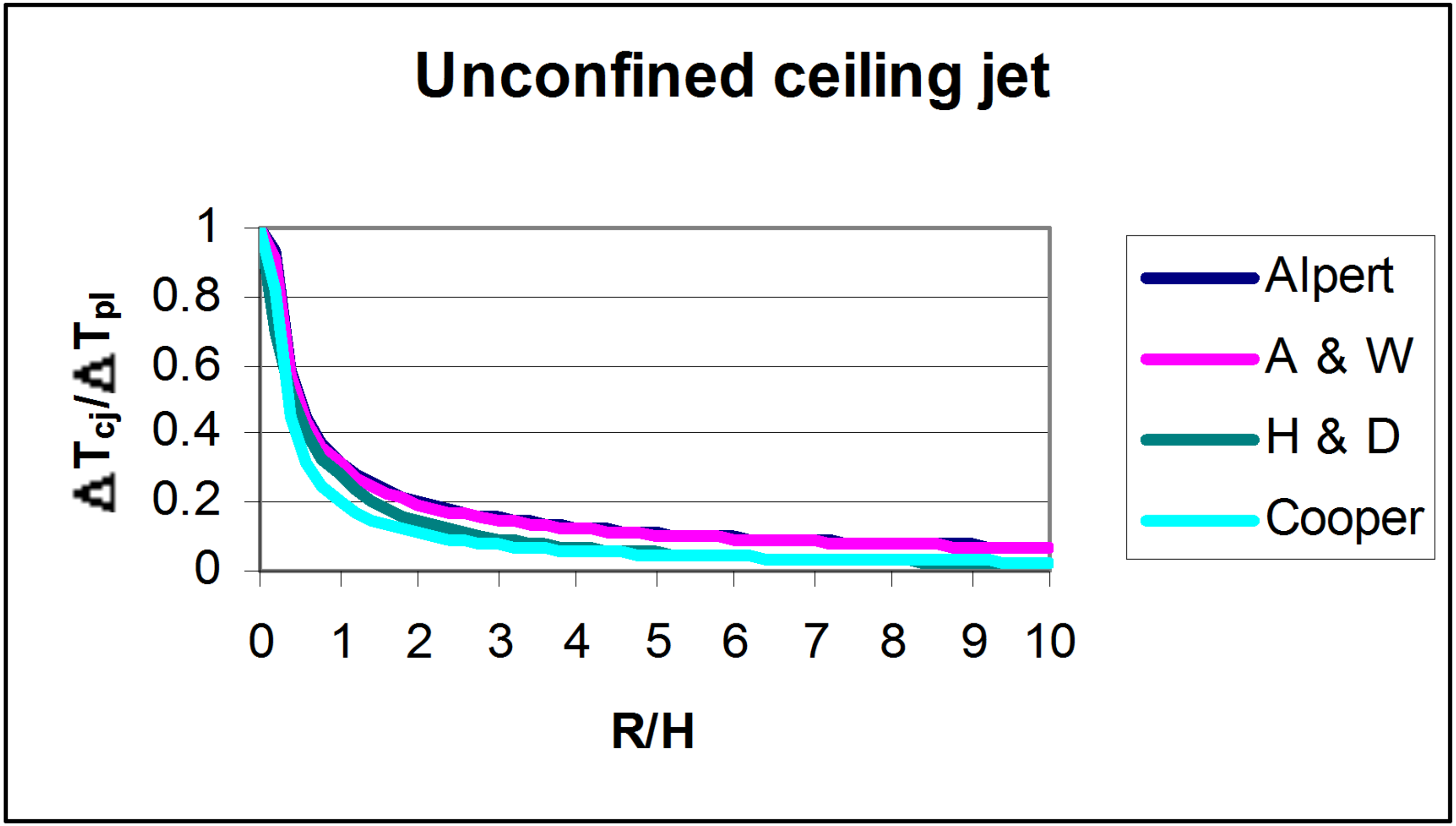
- Temperature correlations
  - Alpert

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.32}{\left(R/H\right)^{2/3}} \qquad \Delta T_{pl} = 16.9\frac{\dot{Q}^{2/3}}{H^{5/3}}$$

  - Heskestad and Delichatsios

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.11}{\left(0.188 + 0.313R/H\right)^{4/3}} \qquad \Delta T_{pl} = 25\frac{\dot{Q}^{2/3}}{H^{5/3}}$$

Temperature correlations

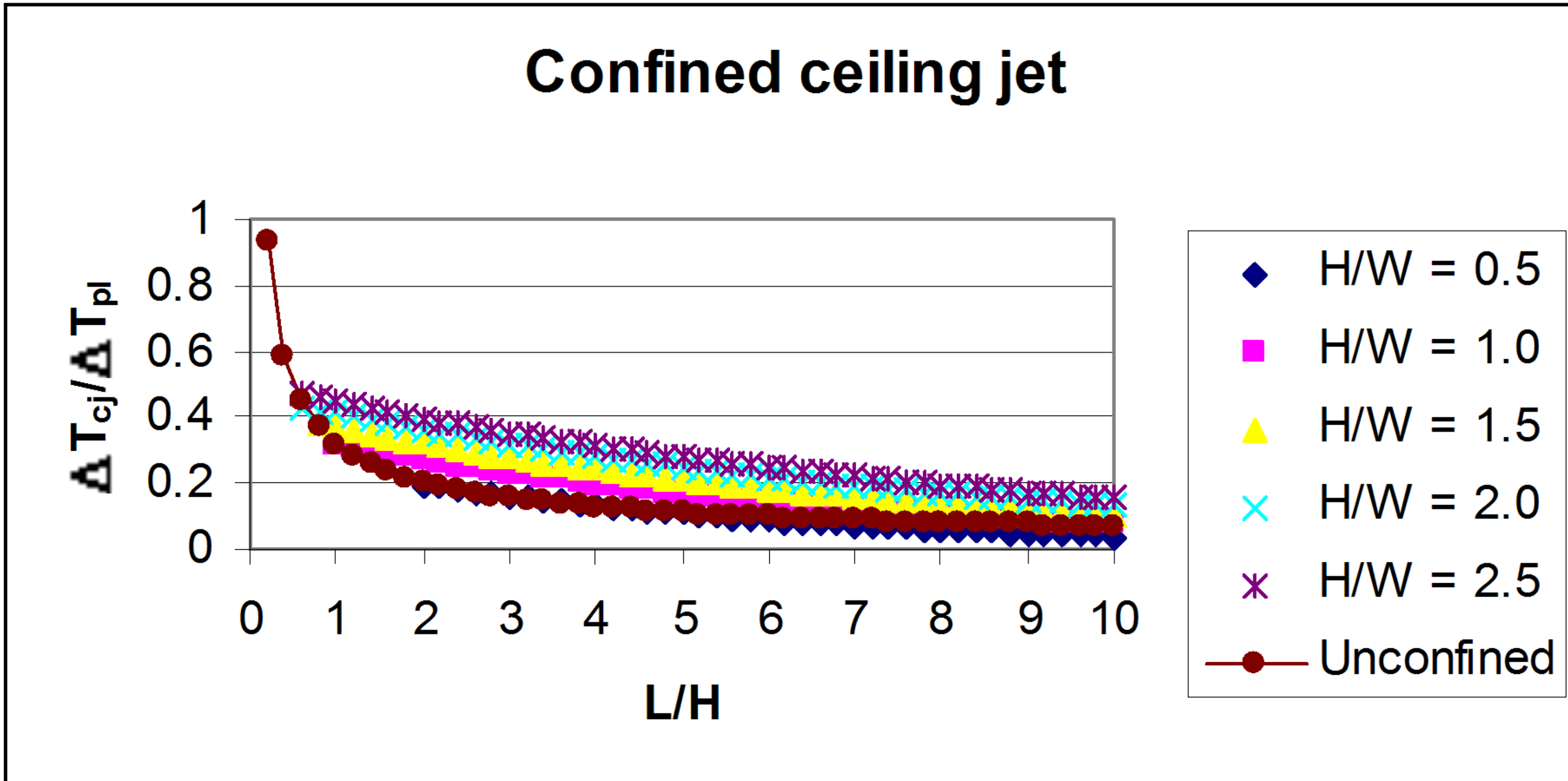


Confined ceiling jet

- Temperature correlation
  - Delichatsios

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = 0.37\left[\frac{H}{W}\right]^{1/3} \exp\left[-0.16\left(\frac{L}{H}\right)\left(\frac{W}{H}\right)^{1/3}\right]$$

Ceiling jet temperatures



Unconfined ceiling jet

- Velocity correlations
  - Alpert

$$\frac{u}{u_o} = \frac{0.2}{(R/H)^{5/6}}$$

  - Heskestad and Delichatsios

$$\frac{u}{u_o} = \frac{0.18}{(R/H)^{0.63}(0.188 + 0.313R/H)^{2/3}}$$

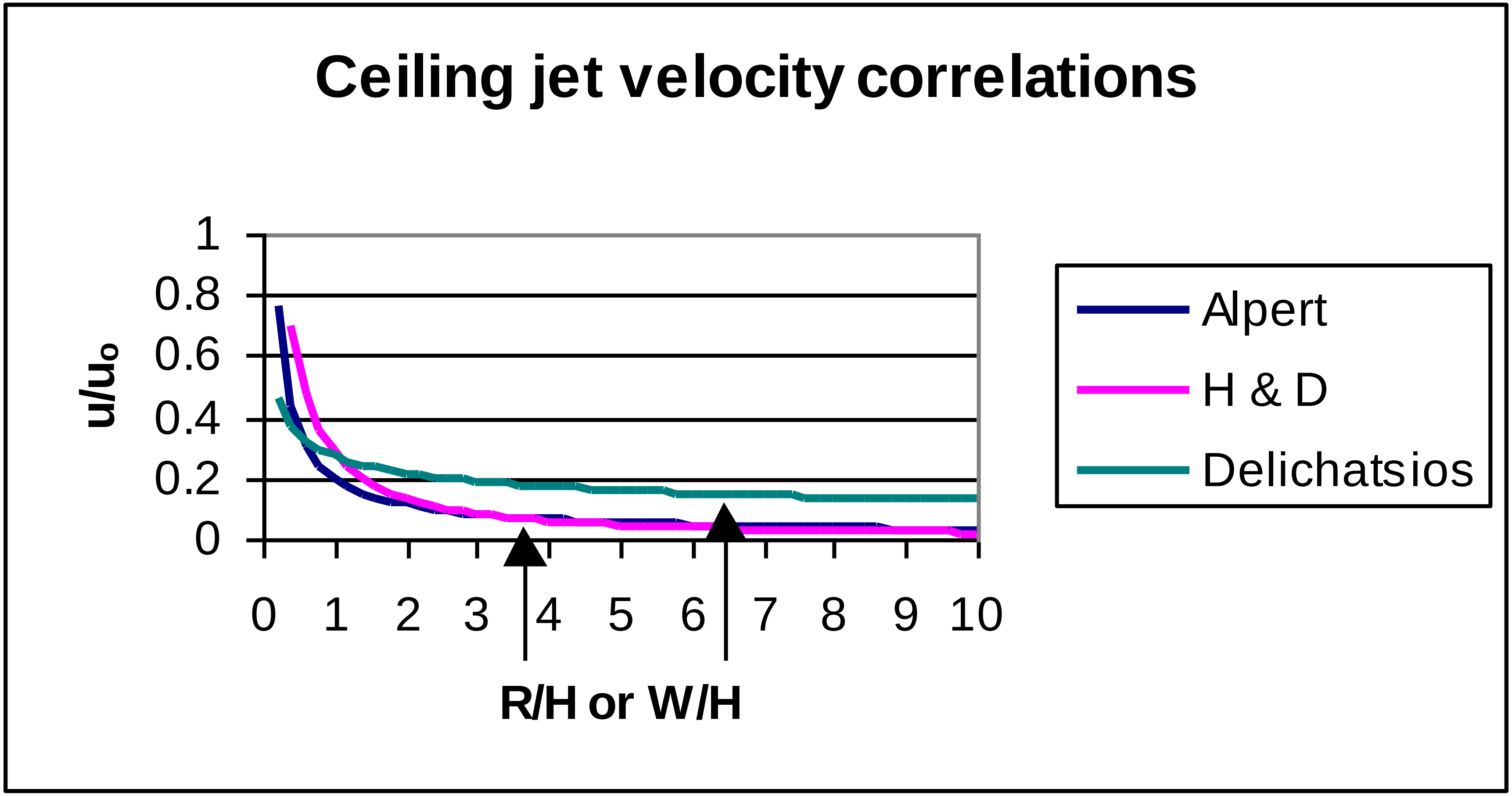
Confined ceiling jet

- Velocity correlation
  - Delichatsios

$$\frac{u}{u_o} = \frac{0.27}{(W/H)^{1/3}}$$

  - Note that according to this correlation the velocity does not change as the flow moves down the corridor

Ceiling jet velocities

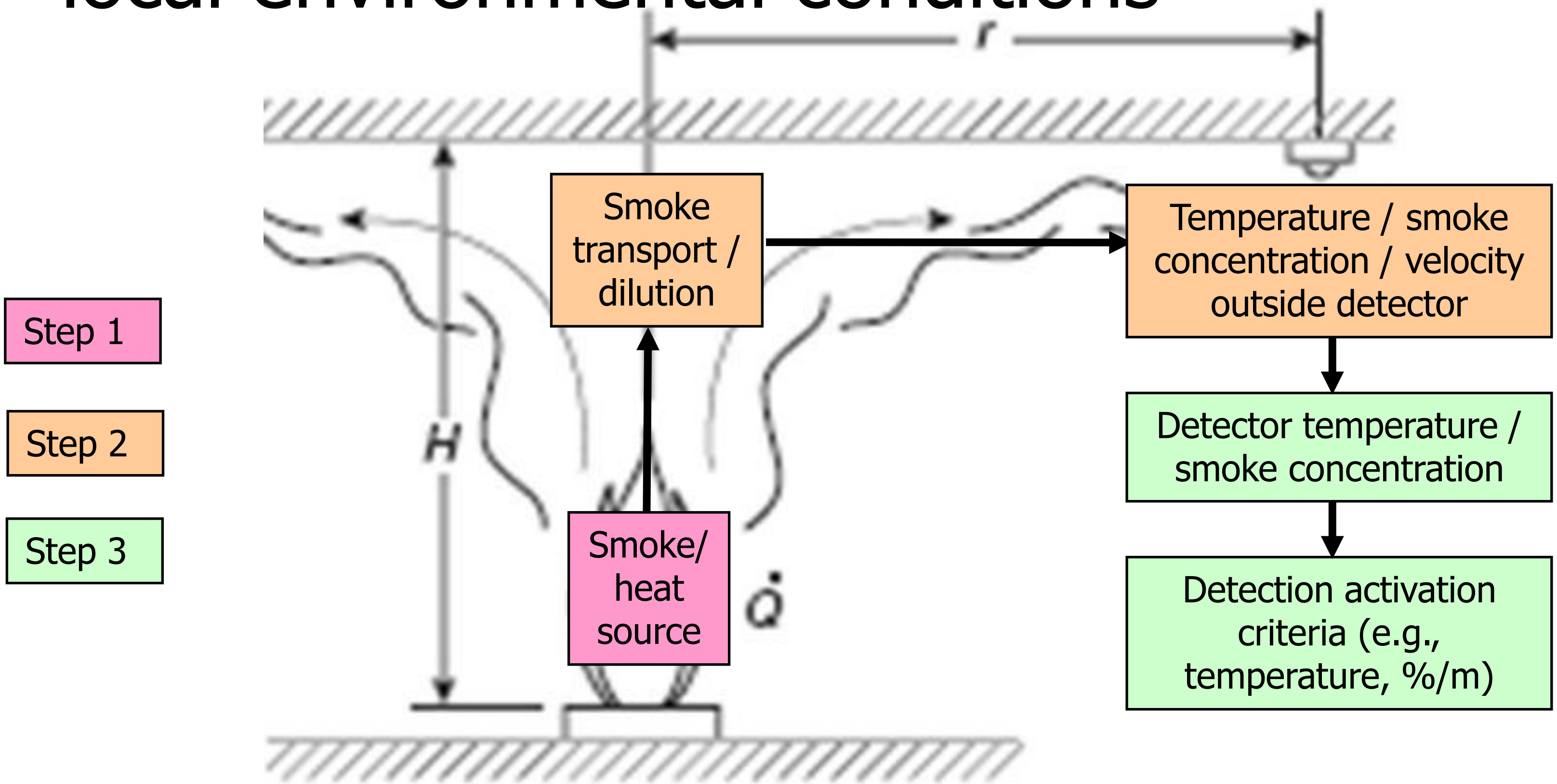


Heat and smoke detection

- Understand terminology used to describe the activation of fire detection devices
- Appreciate the role of different variables in estimating fire detector activation and structural damage times
- Calculate the response of fire detectors to fire plume and ceiling jet conditions

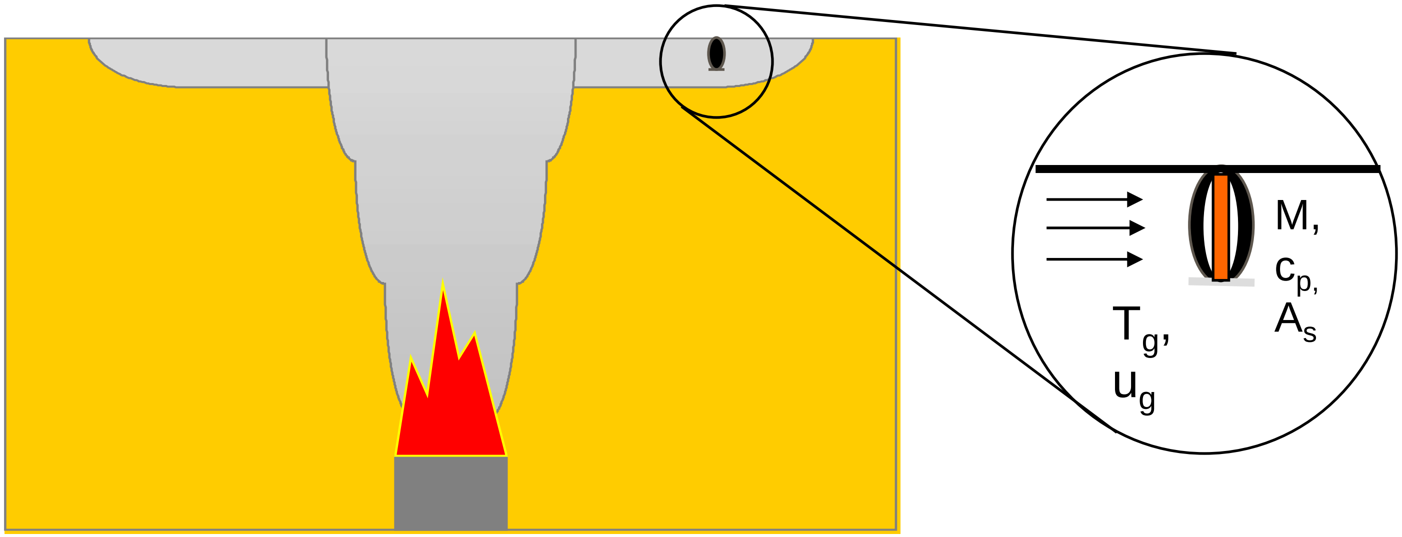
Overview

- Step 3. Calculate detector response to local environmental conditions



The DETACT model

- A first order response model for predicting fire detector activation based on convective heating and a lumped capacity analysis



Bases

- Heat balance at detector $\dot{q}_{abs} = \dot{q}_{in} - \dot{q}_{out}$
- Convective heating only $\dot{q}_{in} = h_c A_s (T_g - T_d)$
- Lumped capacity analysis $\dot{q}_{abs} = mc_p \dfrac{dT_d}{dt}$
- Negligible losses (basic model) $\dot{q}_{out} \approx 0$

Solution

- Predictive equation for temperature rise

$$\frac{dT_d}{dt} = \frac{h_c A_s}{mc_p}(T_g - T_d) = \frac{(T_g - T_d)}{\tau}$$

- Definition of detector time constant

$$\tau \equiv \frac{mc_p}{h_c A_s}$$

  - Time constant not really constant because it depends on heat transfer coefficient, which depends on gas velocity

DETACT formulation

- *Euler* equation for T_d

$$T_d^{(t+\Delta t)} = T_d^{(t)} + \frac{dT_d}{dt}\Delta t$$

- Substitute equation for dT_d/dt

$$T_d^{(t+\Delta t)} = T_d^{(t)} + \frac{\sqrt{u_g^{(t)}}}{RTI}\left(T_g^{(t)} - T_d^{(t)}\right)\Delta t$$

- Evaluation requires RTI, T_g(t) and u_g(t)

Detector activation

- Fixed temperature devices $T_d > T_{act} \Rightarrow t_{act}$
- Rate-of-rise devices $\dfrac{dT_d}{dt} > \dfrac{dT_{act}}{dt} \Rightarrow t_{act}$
  - Typical value of dT_{act}/dt: 8.3ºC (15 ºF) /min

Sprinkler activation

- Generic sprinkler temperature ratings
  - From NUREG 1805

Table 10-2. Generic Sprinkler Temperature Rating ($T_{activation}$)

Temperature Classification	Range of Temperature Ratings °C (°F)	Generic Temperature Ratings °C (°F)
Ordinary	57–77 (135–170)	74 (165)
Intermediate	79–107 (175–225)	100 (212)
High	121–149 (250–300)	135 (275)
Extra high	163–191 (325–375)	177 (350)
Very extra high	204–246 (400–475)	232 (450)
Ultra high	260–302 (500–575)	288 (550)
Ultra high	343 (650)	288 (550)

Sprinkler activation

- Generic sprinkler RTIs
  - From NUREG 1805

Table 10-3. Generic Sprinkler Response Time Index (RTI)

Common Sprinkler Type	Generic Response Time Index RTI $(m\text{-}sec)^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34

Heat detector activation

- Generic heat detector RTIs
  - From NFPA 72

UL Listed Spacing	UL Listed Activation Temperature						All FM Listed Temps.
(ft/m)	128°F (53°C)	135°F (57°C)	145°F (63°C)	160°F (71°C)	170°F (77°C)	196°F (91°C)	
10/3.1	894/494	738/408	586/324	436/241	358/198	217/120	436/241
15/4.6	559/309	425/235	349/193	246/136	199/110	101/56	246/136
20/6.1	369/204	302/167	235/130	157/87	116/64	38/21	157/87
25/7.6	277/153	224/124	174/96	107/59	72/40	---	107/59
30/9.2	212/117	179/99	136/75	81/45	49/27	---	81/45
40/12.2	159/88	128/71	92/51	40/22	---	---	
50/15.3	132/73	98/54	67/37	---	---	---	
70/21.4	81/45	54/30	20/11	---	---	---	

Notes: 1. RTIs are shown in $(\text{ft-s})^{1/2}/(\text{m-s})^{1/2}$

Smoke detector activation

- Heat detector analogy
  - Treat smoke detector as low RTI device
    - Cannot use zero - Divide by zero error
    - Hand calculations - use $T_d = T_g$
  - Assume $\Delta T_{act} \sim 15^{o}C$ (or less)
  - Questions regarding validity
    - Relies on optical density analogy
    - Smoke detectors don’t always respond to optical density

Smoke detector activation

- Smoke concentration in detector chamber, Y_c
  - Cleary's four-parameter model

$$\frac{dY_c}{dt} = \frac{Y_s(t-\delta t_e) - Y_c(t)}{\delta t_c} \qquad \delta t_e = \alpha_e u^{\beta_e}; \delta t_c = \alpha_c u^{\beta_c}$$

  - Heskestad's one-parameter model

$$\frac{dY_c}{dt} = \frac{Y_s(t) - Y_c(t)}{\delta t_c} \qquad \delta t_c = L/u$$

    - u is the local gas velocity outside the detector
    - L is the characteristic entry length of the detector

Structural steel damage

- Same concept as DETACT for steel

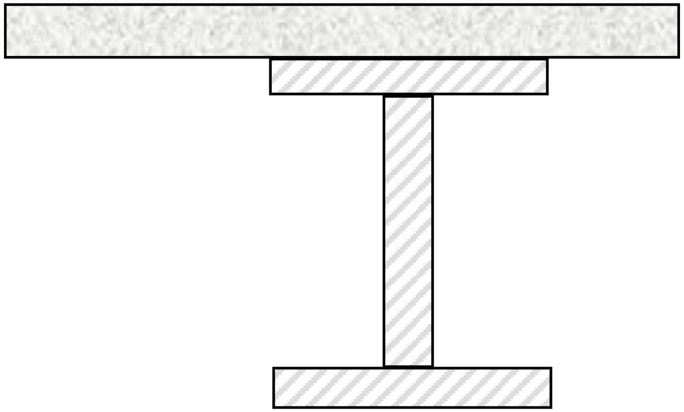
$$\frac{dT_s}{dt} = \frac{\dot{q}_t A_s}{\rho V c_p} = \frac{\dot{q}_t}{\rho c_p (V/A_s)} = \frac{\dot{q}_t}{c_p (W/D)}$$

- Steel properties

$$\rho c_p \approx 3{,}666 (kJ/m^3K)$$

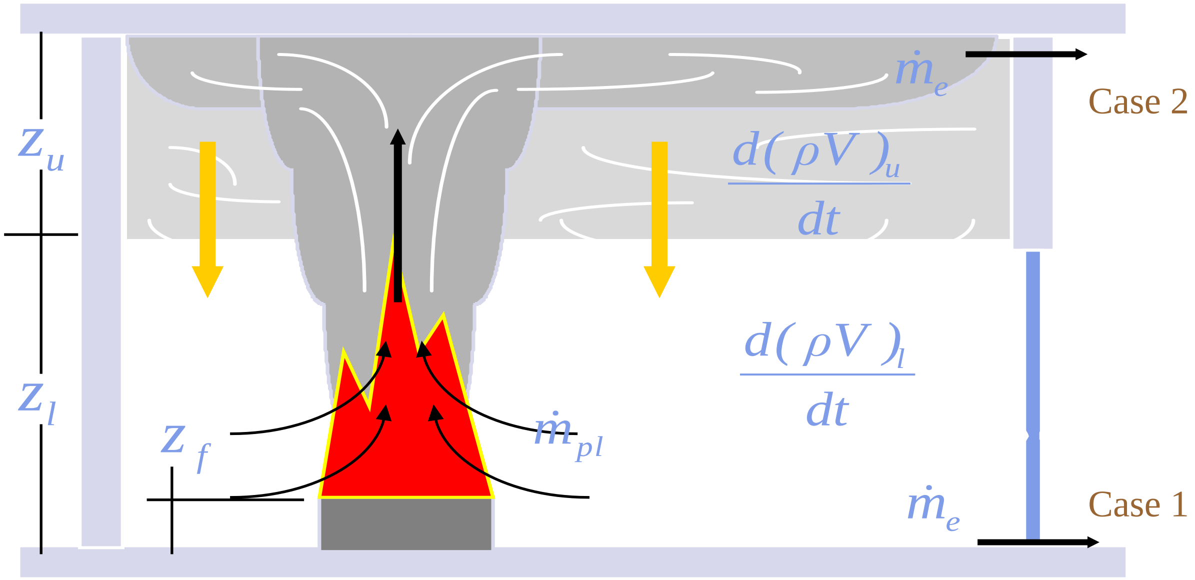
$$\frac{V}{A_s} = \frac{cross - section}{heated\ perimeter}$$

$$\frac{W}{D} = \frac{Weight/length}{heated\ perimeter}$$

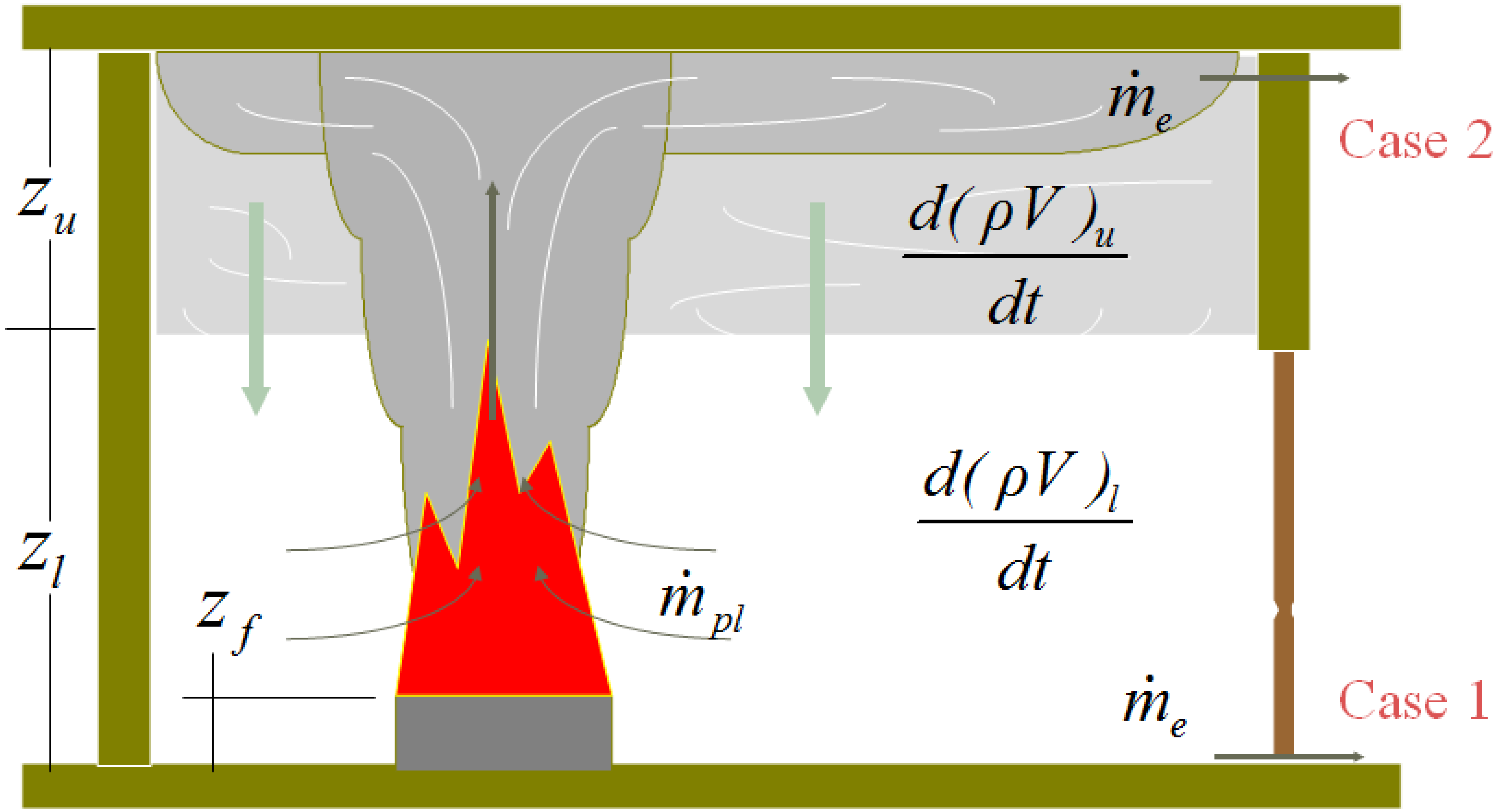


Hot gas layer

- Issues
  - Descent (filling) rate as f(t)
  - Temperature and smoke concentrations
  - Equilibrium position



Enclosure smoke filling



Enclosure smoke filling
Case 2. Small leak at ceiling

- Mass balance on lower layer

$$\frac{d(\rho V)_l}{dt} = \rho_l \frac{dV_l}{dt} = -\dot{m}_{pl}$$

- Volume balance on lower layer

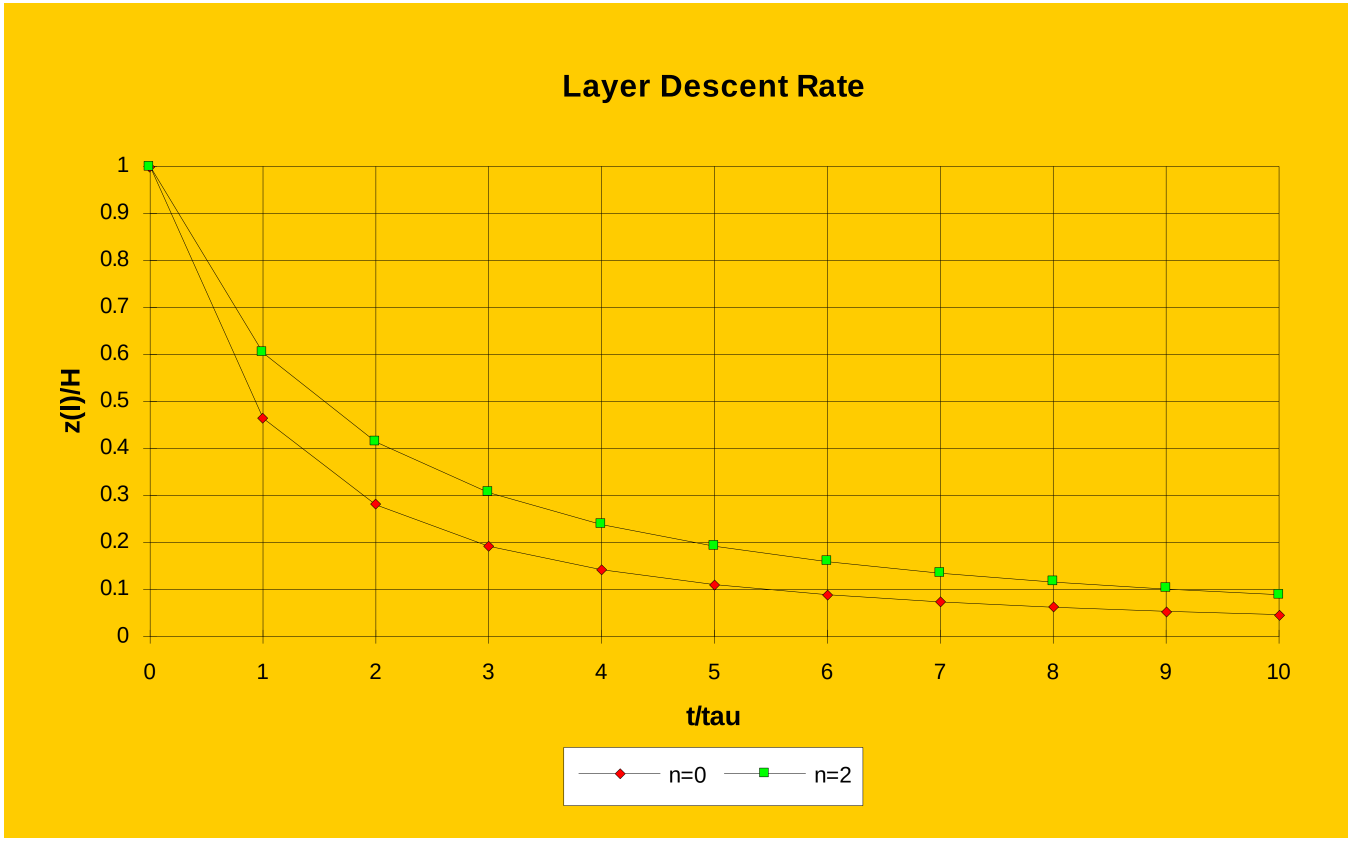
$$\frac{dV_l}{dt} = \frac{-\dot{m}_{pl}}{\rho_l} = -\dot{V}_{pl}$$

- Volume balance on upper layer

$$\frac{dV_u}{dt} = -\frac{dV_l}{dt} = \dot{V}_{pl}$$

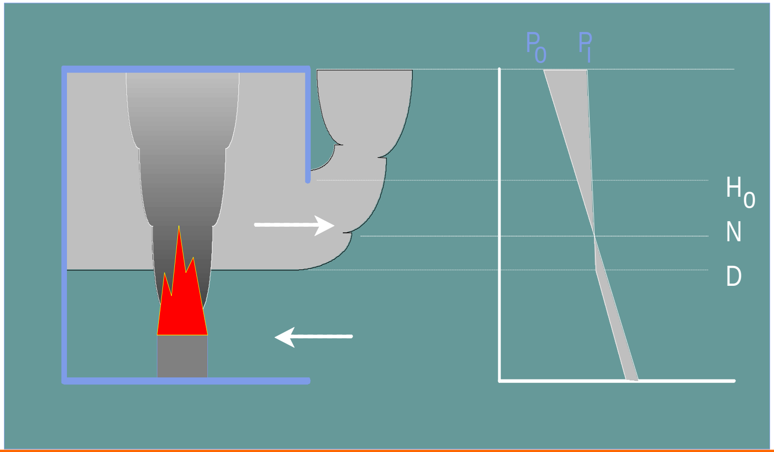
Enclosure smoke filling
Case 2. Small leak at ceiling

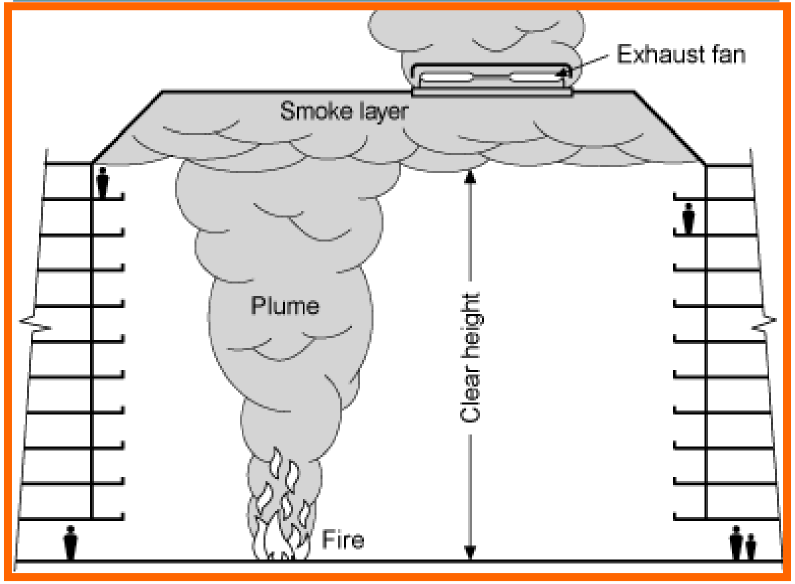
- Solution for smoke layer position - $$\frac{z_u}{H} = 1 - \left[1 + \frac{2t}{(n+3)\tau_v}\right]^{-3/2}$$



Vents/ventilation systems

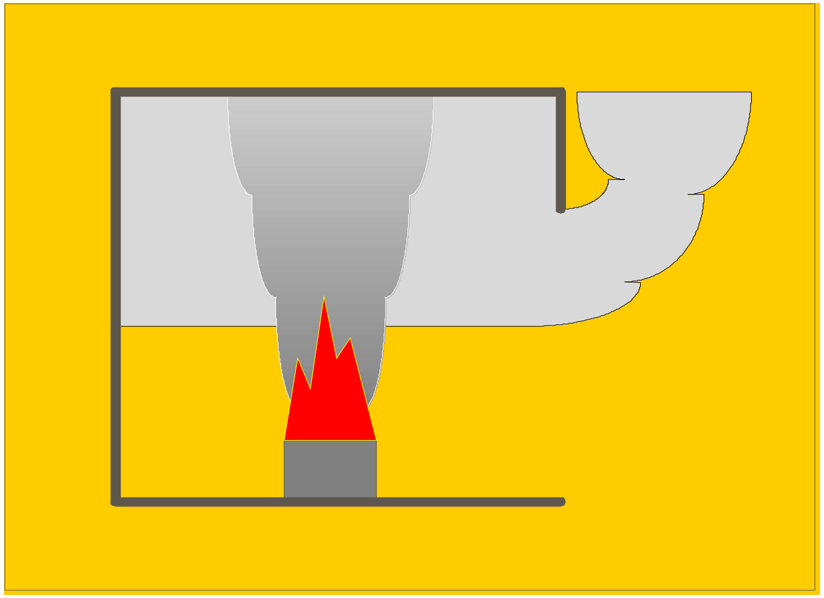
- Types
  - Natural ventilation
    - Wall openings
    - Floor / ceiling openings
  - Mechanical ventilation
    - Injection
    - Extraction
    - Balanced
- Issues
  - Impact on temperature and smoke conditions





Vent flow topics

- Orifice flow equation
  - Application of Bernoulli's equation
- Hydrostatic pressure profiles in room fires
- Roof /floor vents
- Wall vents
  - Ventilation limit
- Multiple vents



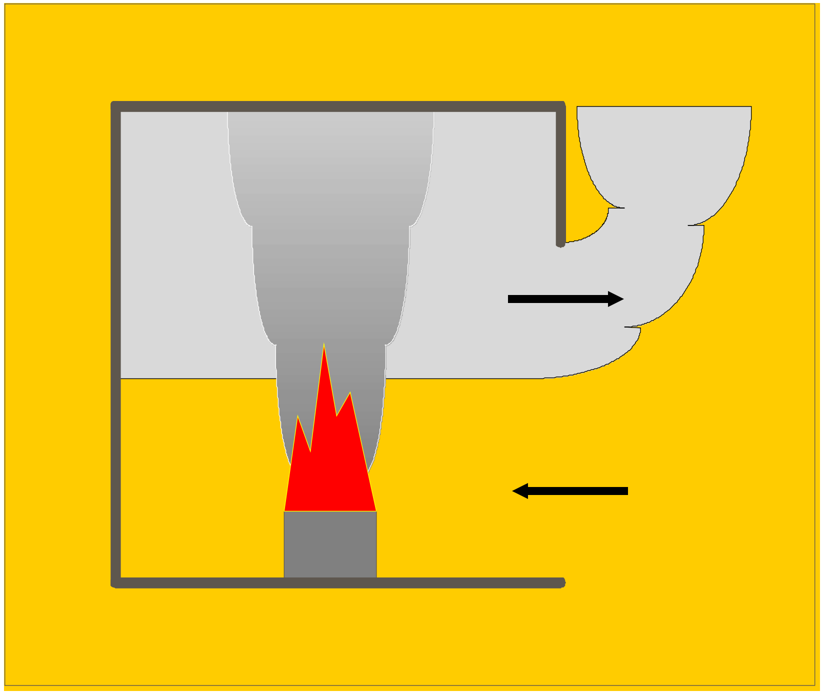
Orifice flow

- Mass flow rate

$$\dot{m} = C_D \rho A v$$

- Velocity

$$v = \sqrt{\frac{2\Delta P}{\rho}}$$



- Need pressure distribution to evaluate mass flow rate

Pressure distribution

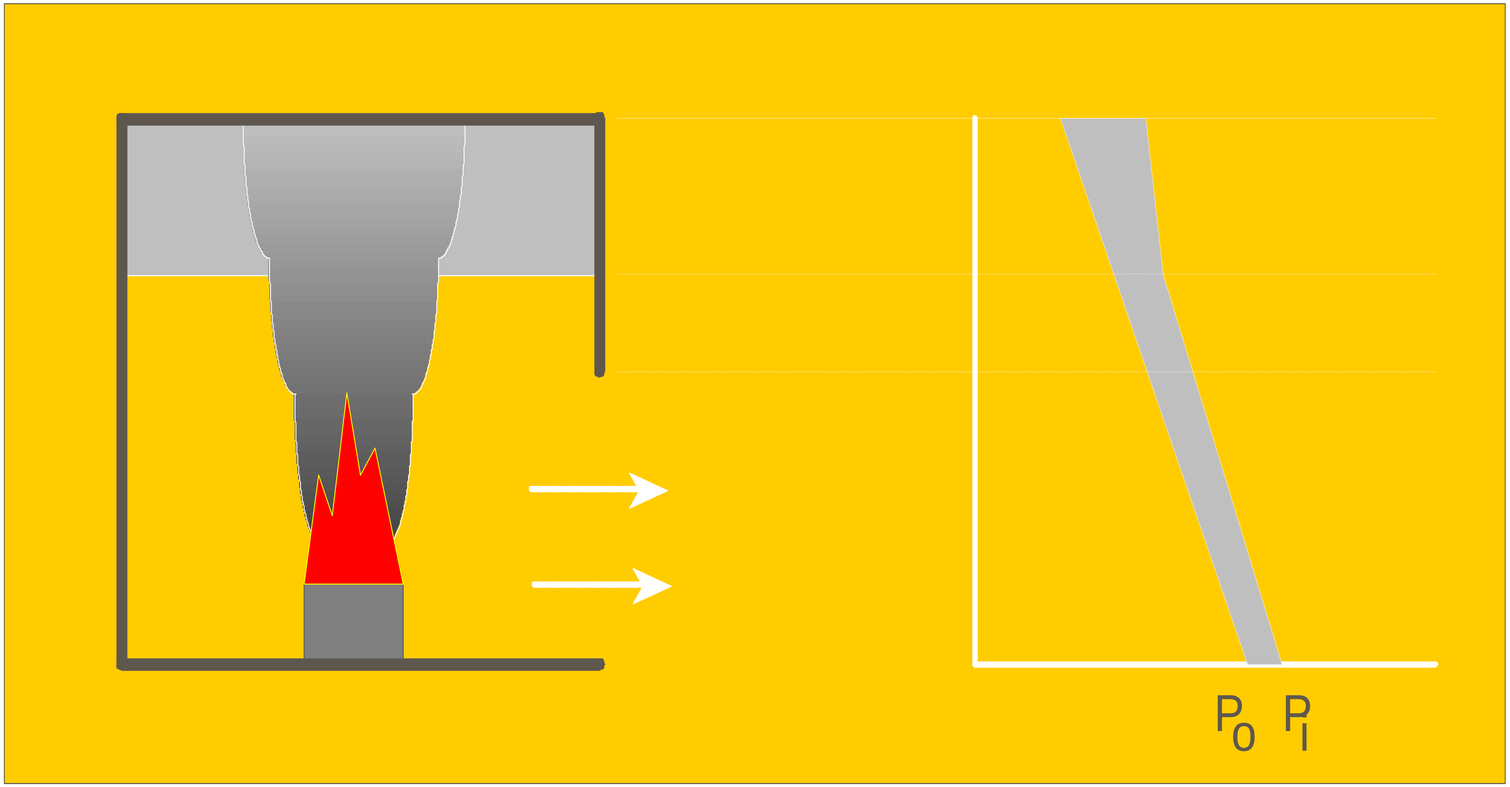
- Pressure differences arise from hydrostatic pressure differences

$$\frac{dP}{dz} = -\rho g = -\frac{\rho_o T_o}{T} g$$

  - Pressure profiles go through series of stages

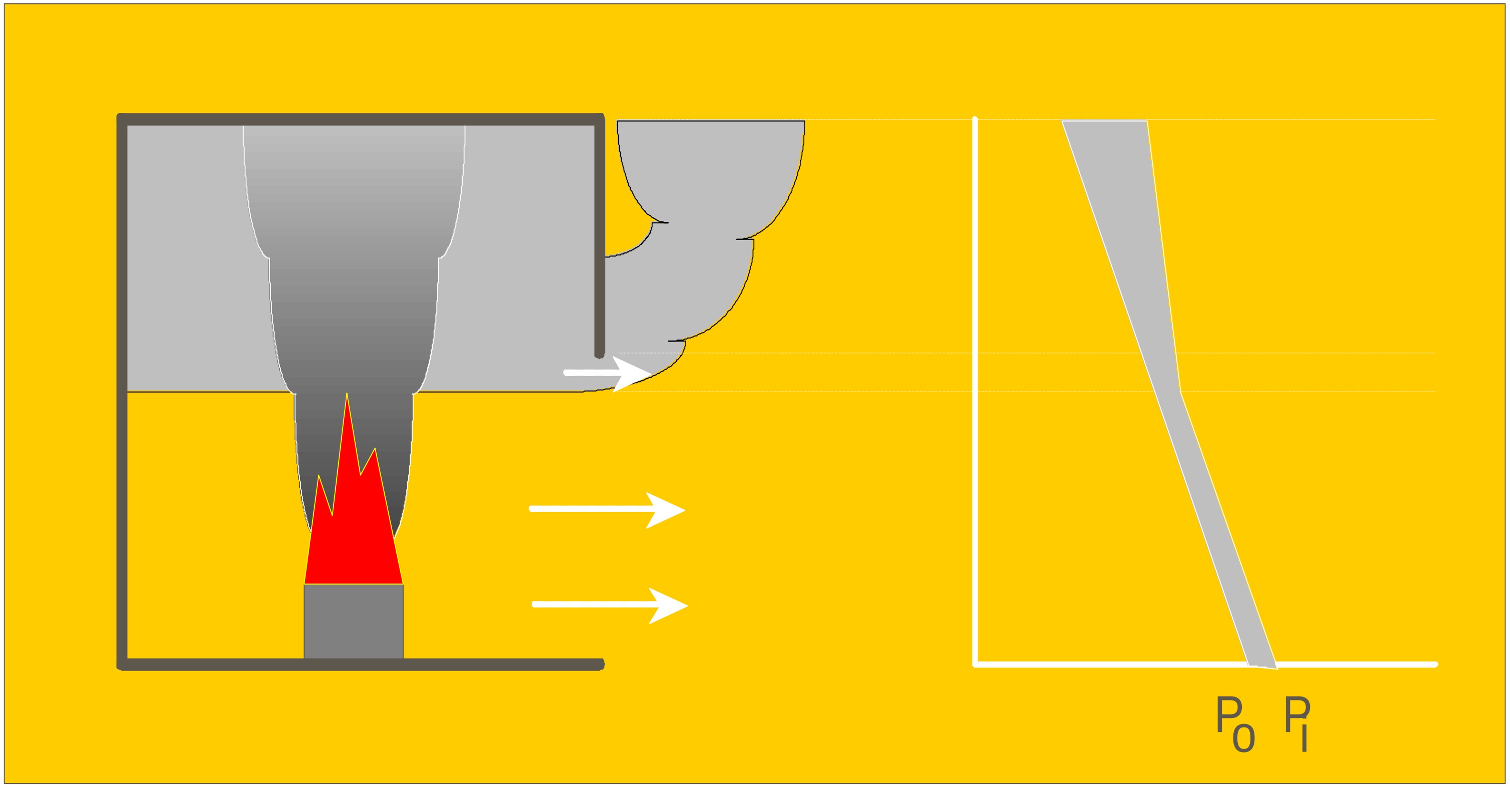
Pressure profile

PHASE 1



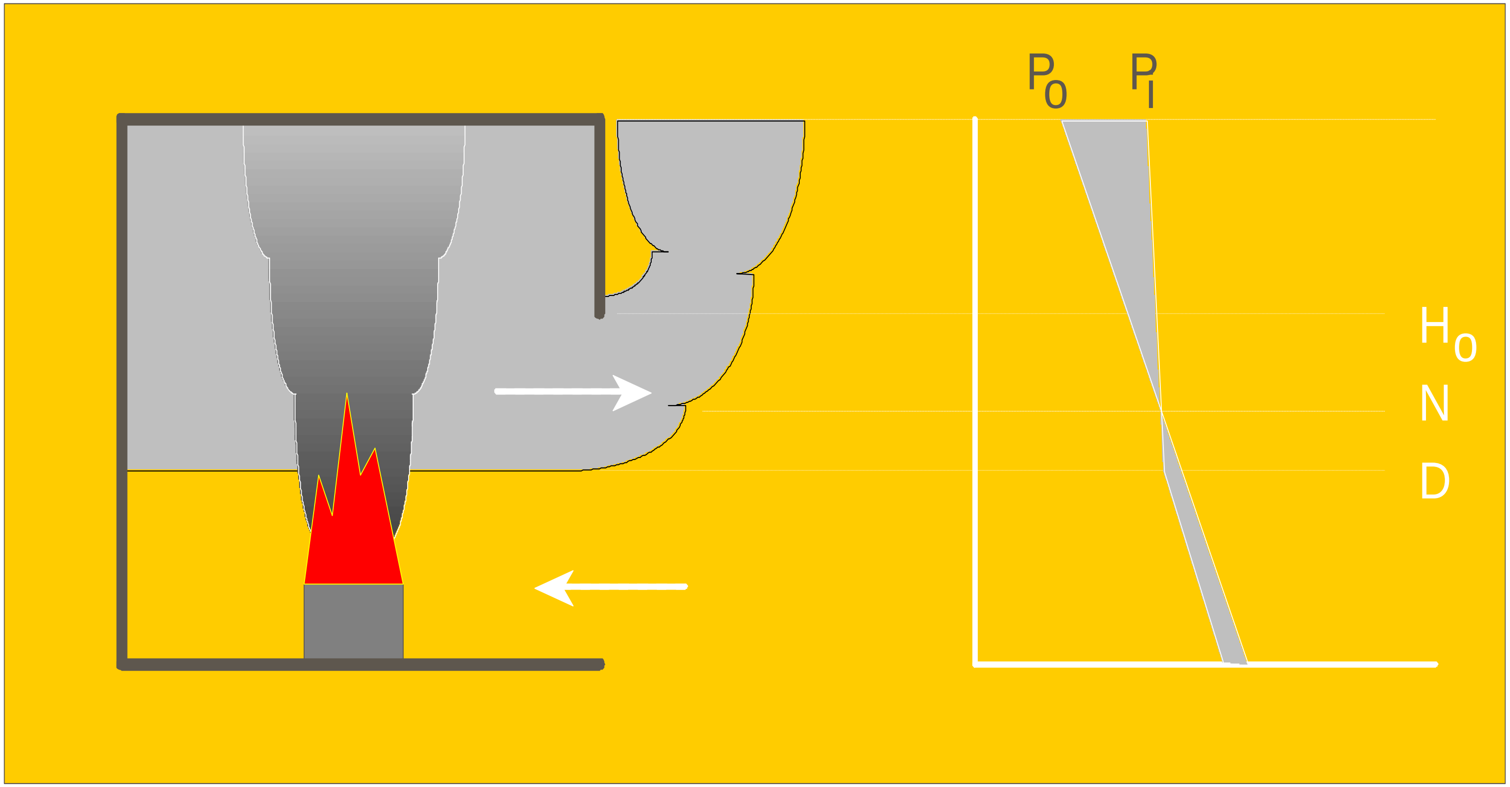
Pressure profile

PHASE 2



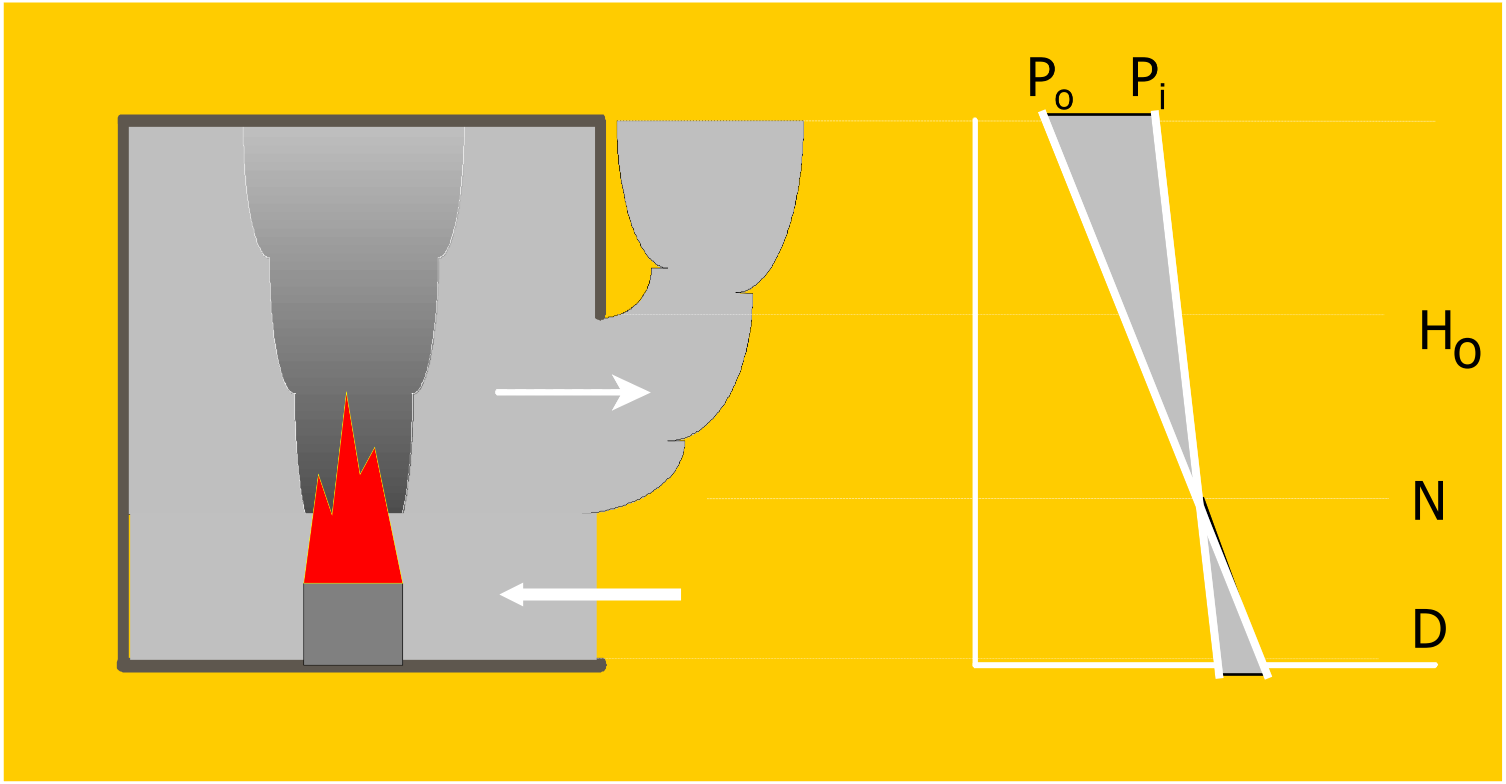
Pressure profile

PHASE 3



Pressure profile

PHASE 4



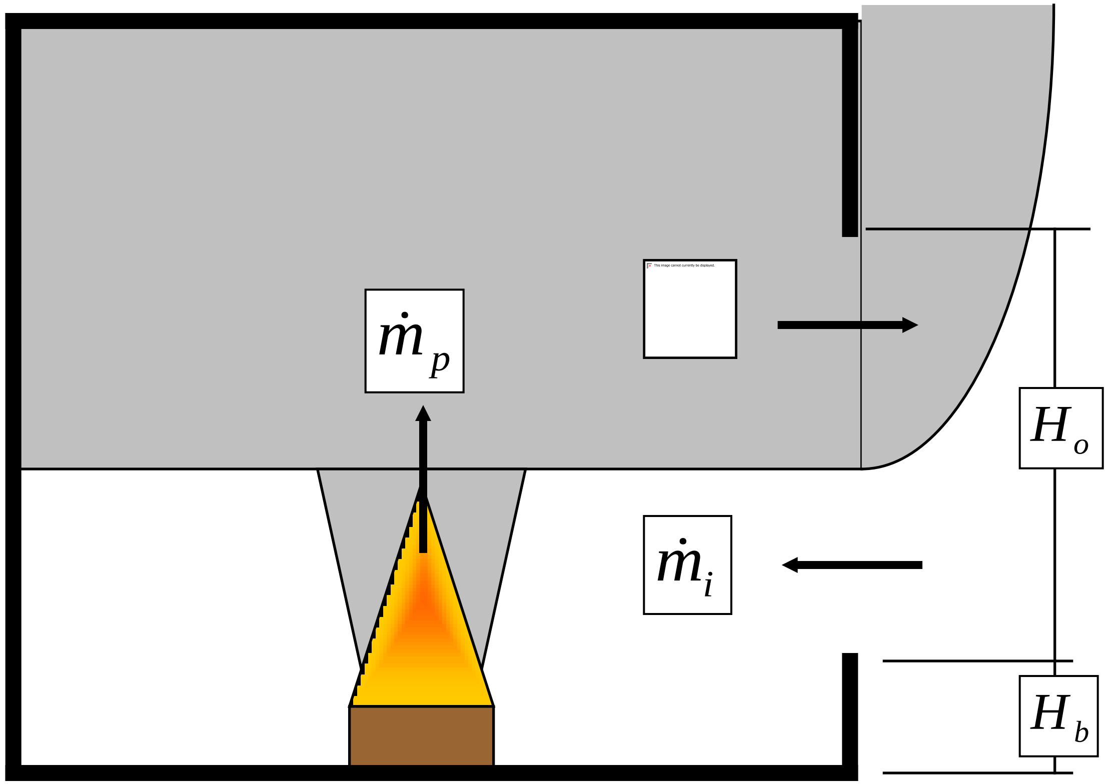
Vent flow cases

- Roof / floor vents
- Wall vents
- Combined / multiple

- One-zone
  - Stack effect
- Two-zone
  - Buoyancy
- Combined
  - Stack + buoyancy

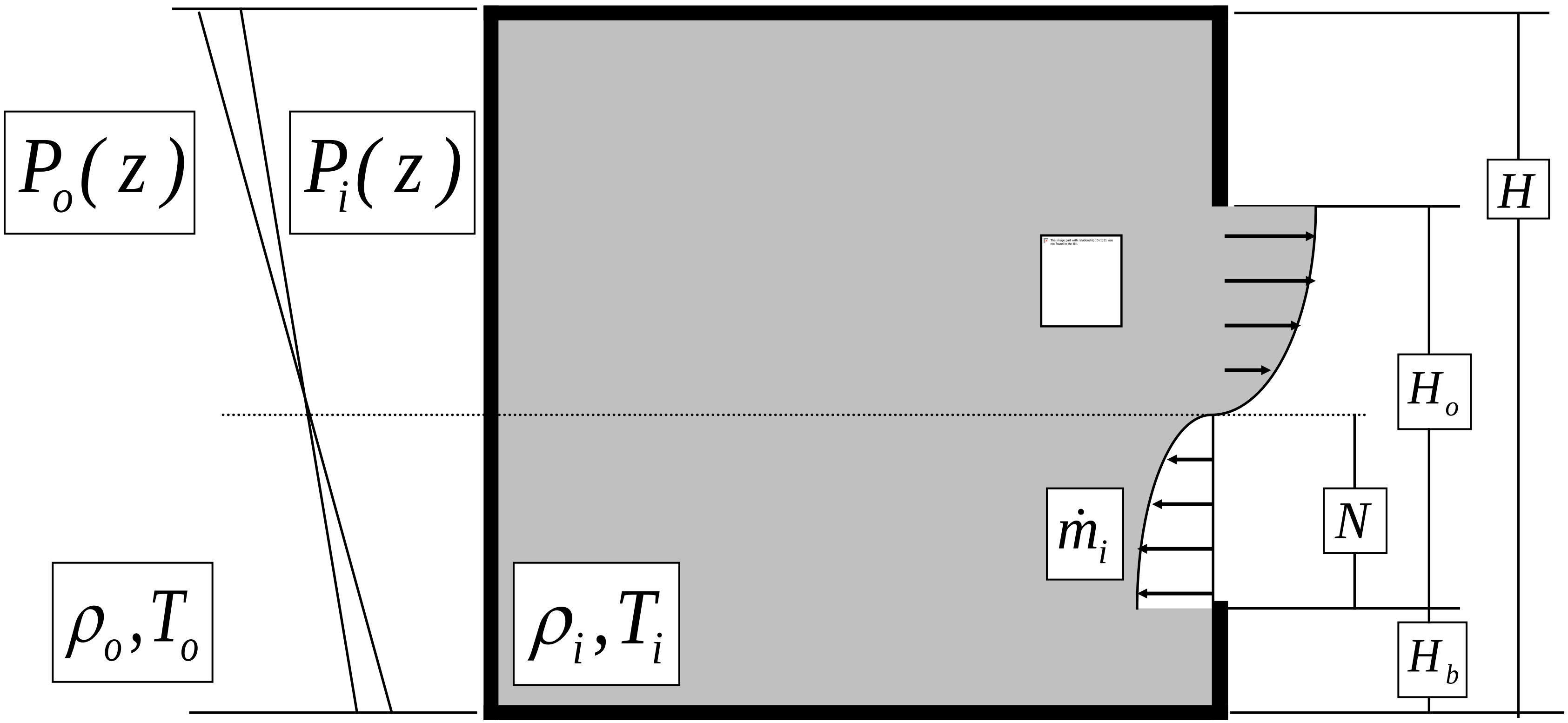
Wall vents

- Bidirectional flow through same vent



Wall vents

- One-zone analysis (Stack only - $T_i > T_o$)



Wall vents

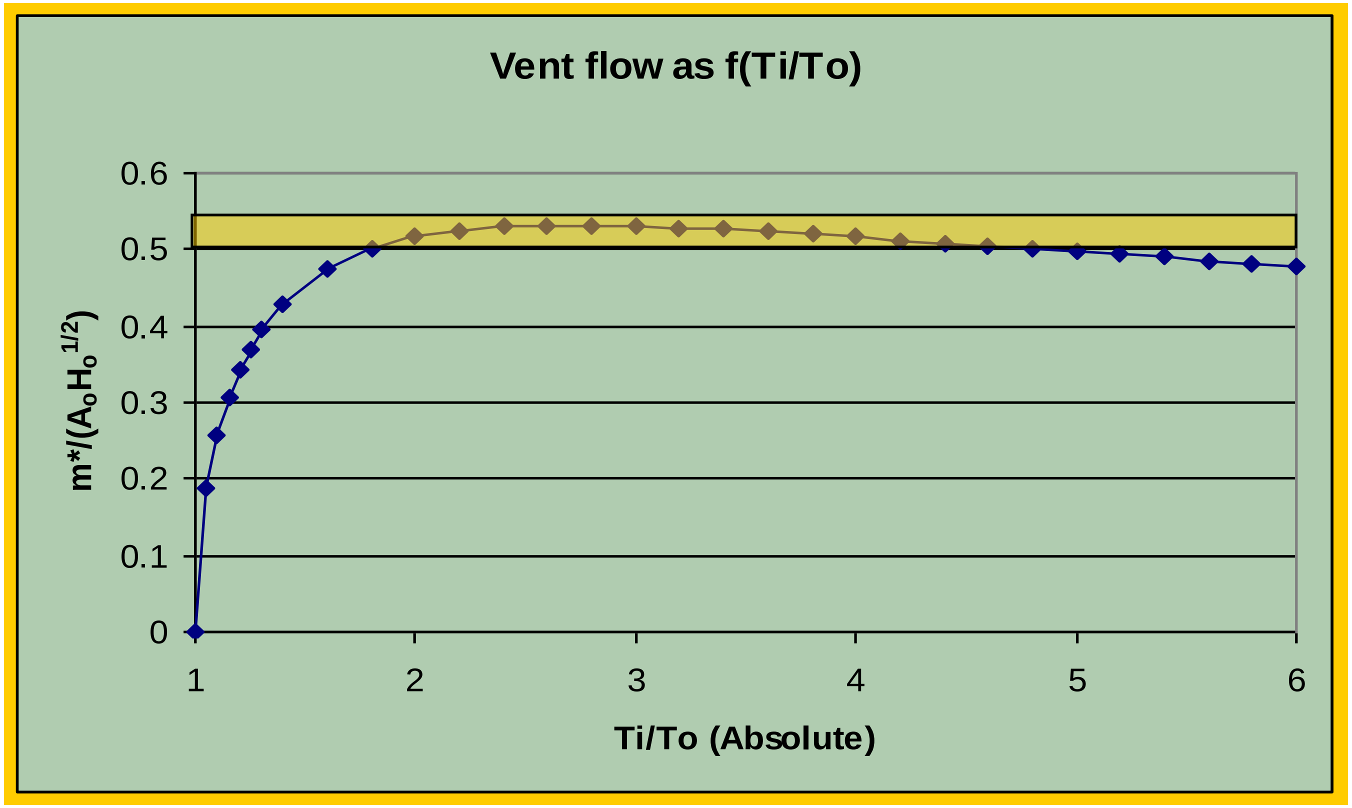
- Substitute into mass outflow equation

$$\dot{m}_o = \frac{2}{3} C_d \rho_o A_o \sqrt{H_o} \sqrt{2g} \left[\frac{T_o}{T_i} \left(1 - \frac{T_o}{T_i} \right) \right]^{1/2} \left(1 - \frac{1}{1 + (T_i / T_o)^{1/3}} \right)^{3/2}$$

  - This is the ventilation limited flow through a single rectangular wall vent
  - Flow is function of ventilation factor and temperature ratio

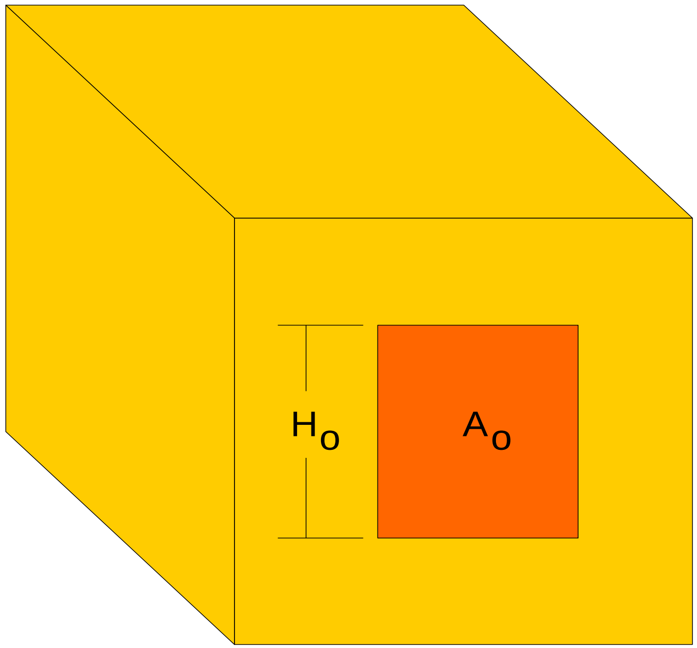
Wall vents

- Plot $$\frac{\dot{m}_o}{A_o\sqrt{H_o}} = f\left(\frac{T_i}{T_o}\right)$$ for $C_d = 0.7$, ambient air



The ventilation limit

- Rooms with single rectangular wall openings



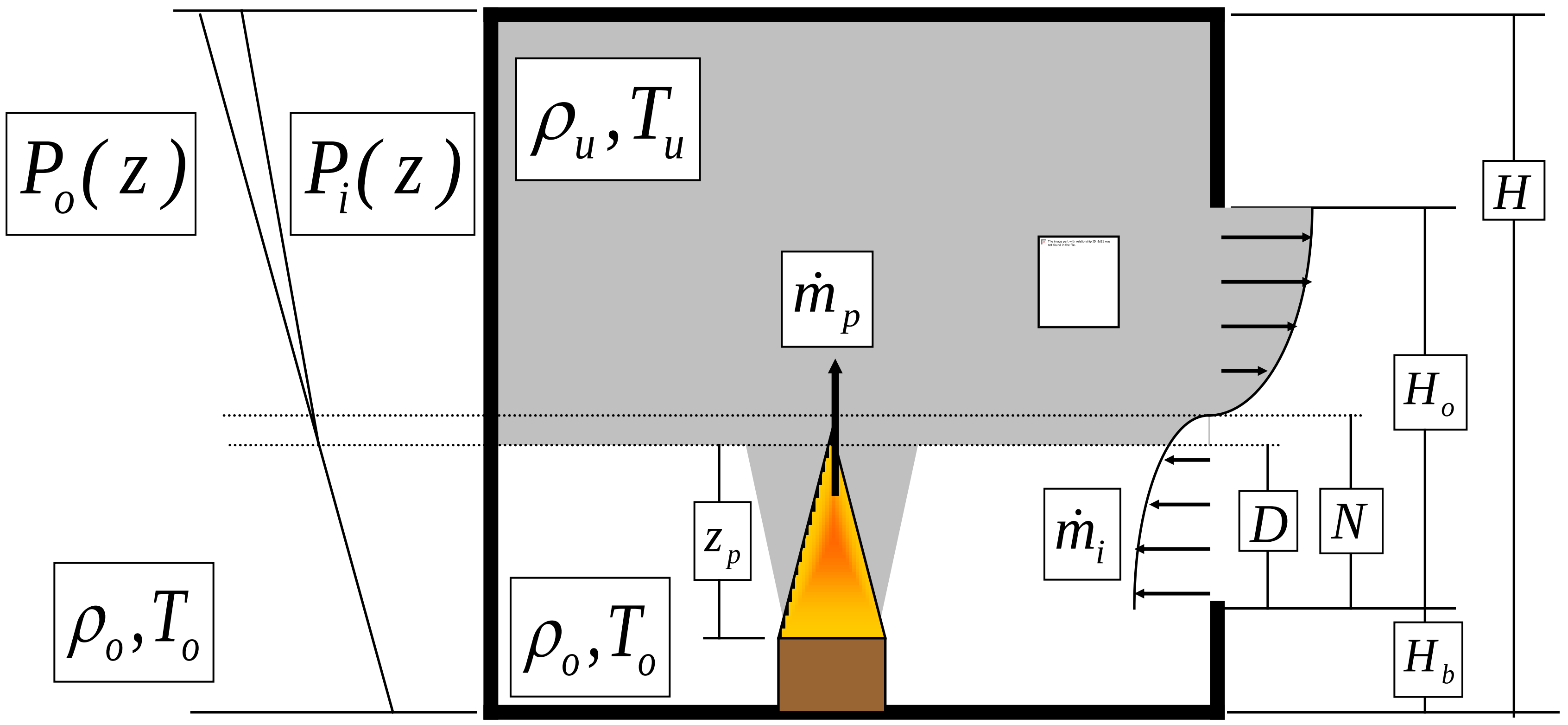
$$\dot{m}_{max} \approx 0.5 A_o \sqrt{H_o}$$

$$\dot{Q}_{max} = \dot{m}_{max} \frac{\Delta H_c}{r}$$

$$\dot{Q}_{max} \approx 1500 A_o \sqrt{H_o}$$

Wall vents

- Two-zone analysis



Wall vents

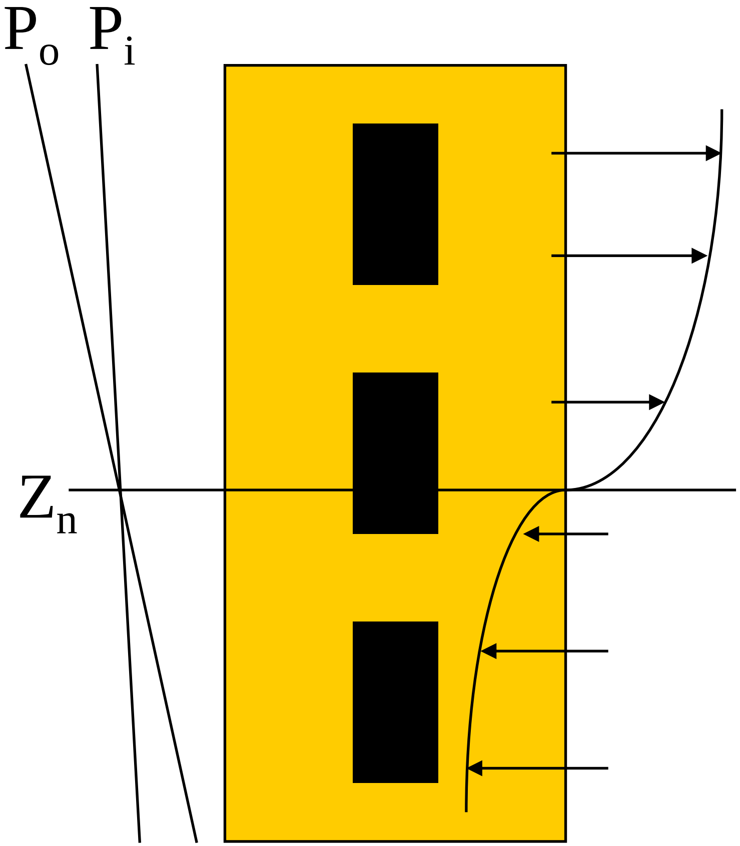
- Two-zone analysis
  - Upper layer analysis same as for one-zone

$$\dot{m}_o = \frac{2}{3} C_D W_o \rho_i \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_i}\right)} \left(H_o - N\right)^{3/2}$$

  - Before onset of ventilation limited conditions, D and N approximately coincident

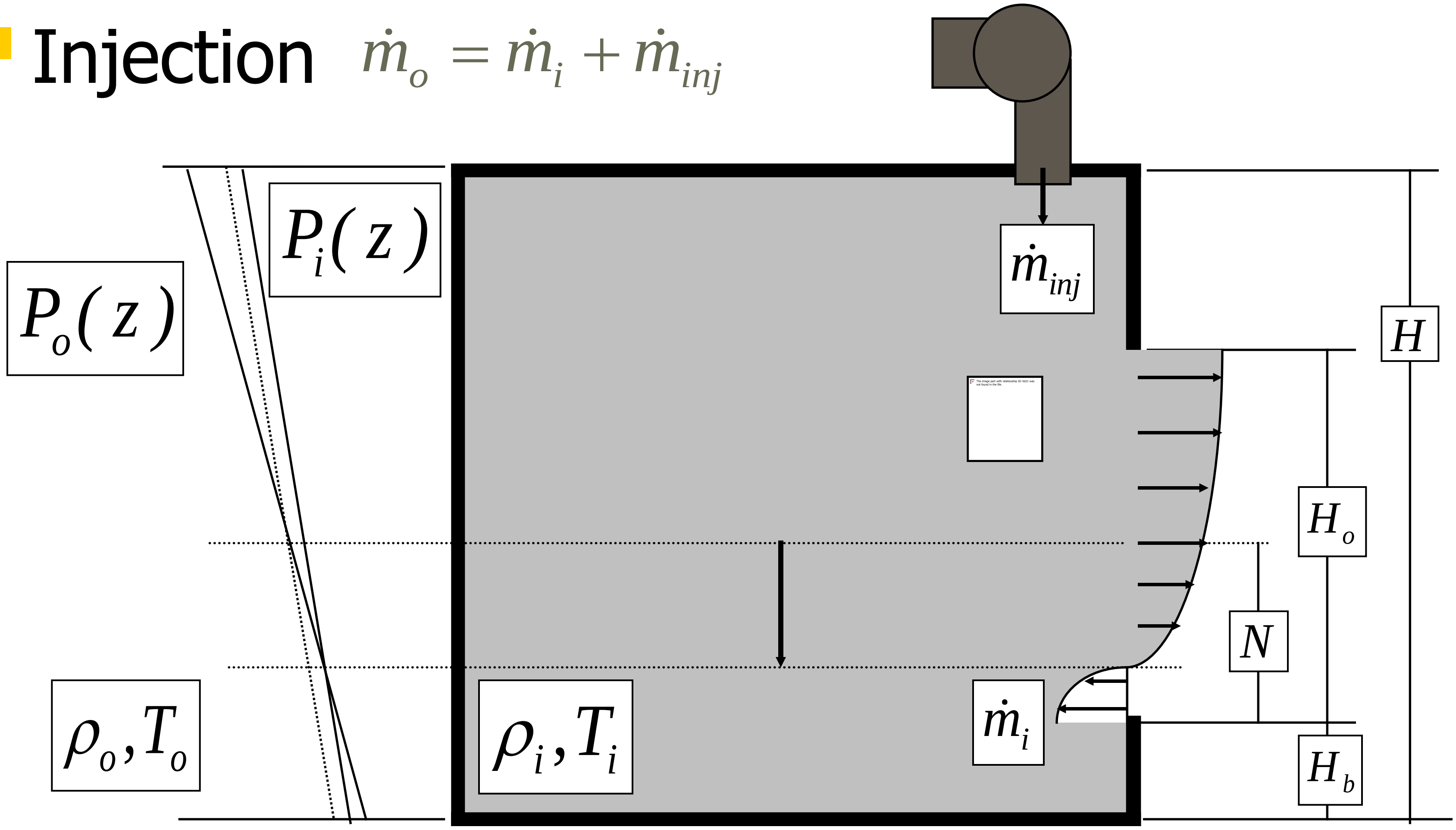
Multiple vents

- Neutral plane occurs where
  - mass inflow = outflow
- Solution technique
  - Guess Z_n
  - Calculate m_o, m_i
  - Compare m_o, m_i
  - If $m_o \neq m_i$, adjust Z_n



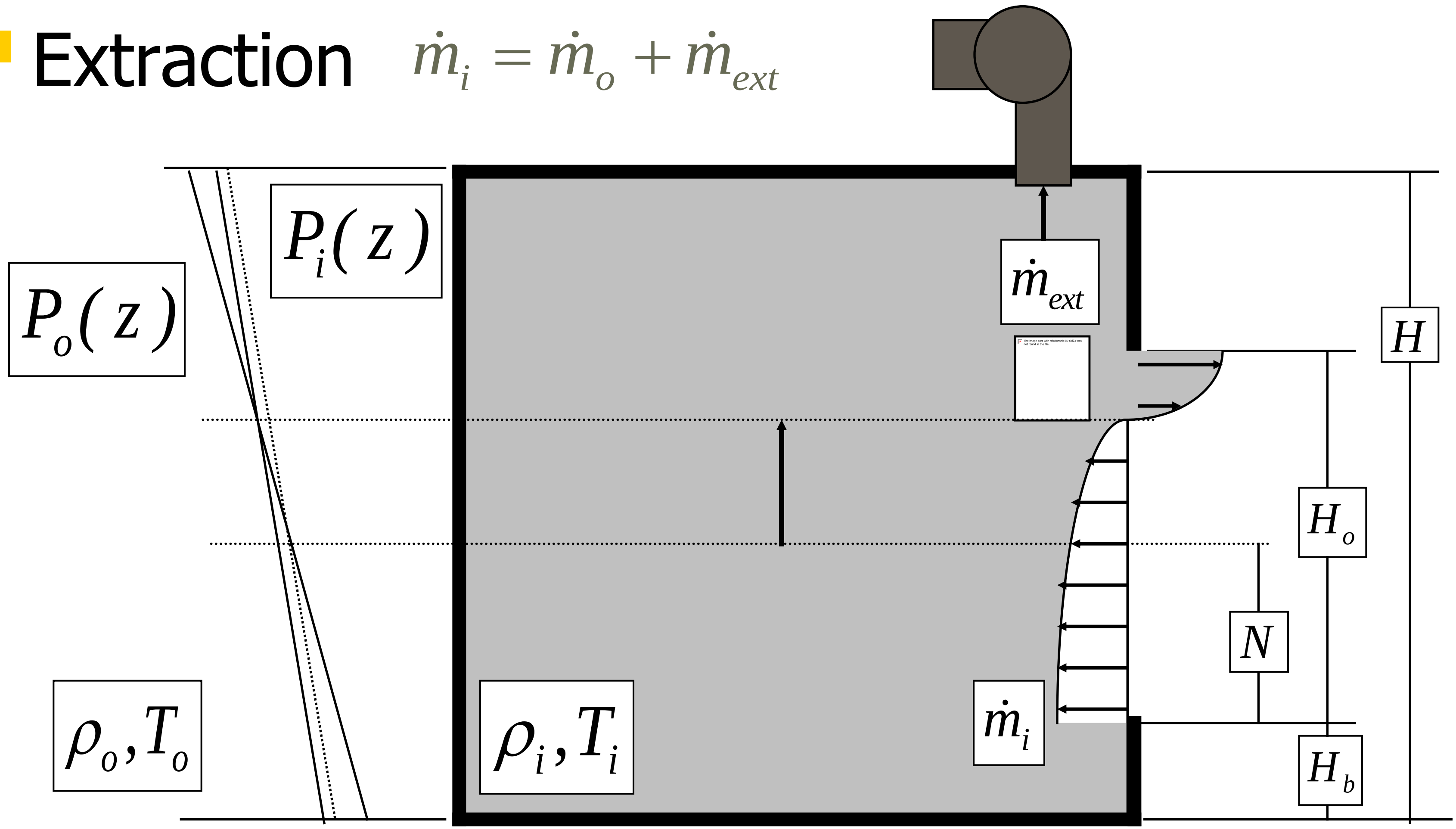
Mechanical ventilation

- Injection $\dot{m}_o = \dot{m}_i + \dot{m}_{inj}$

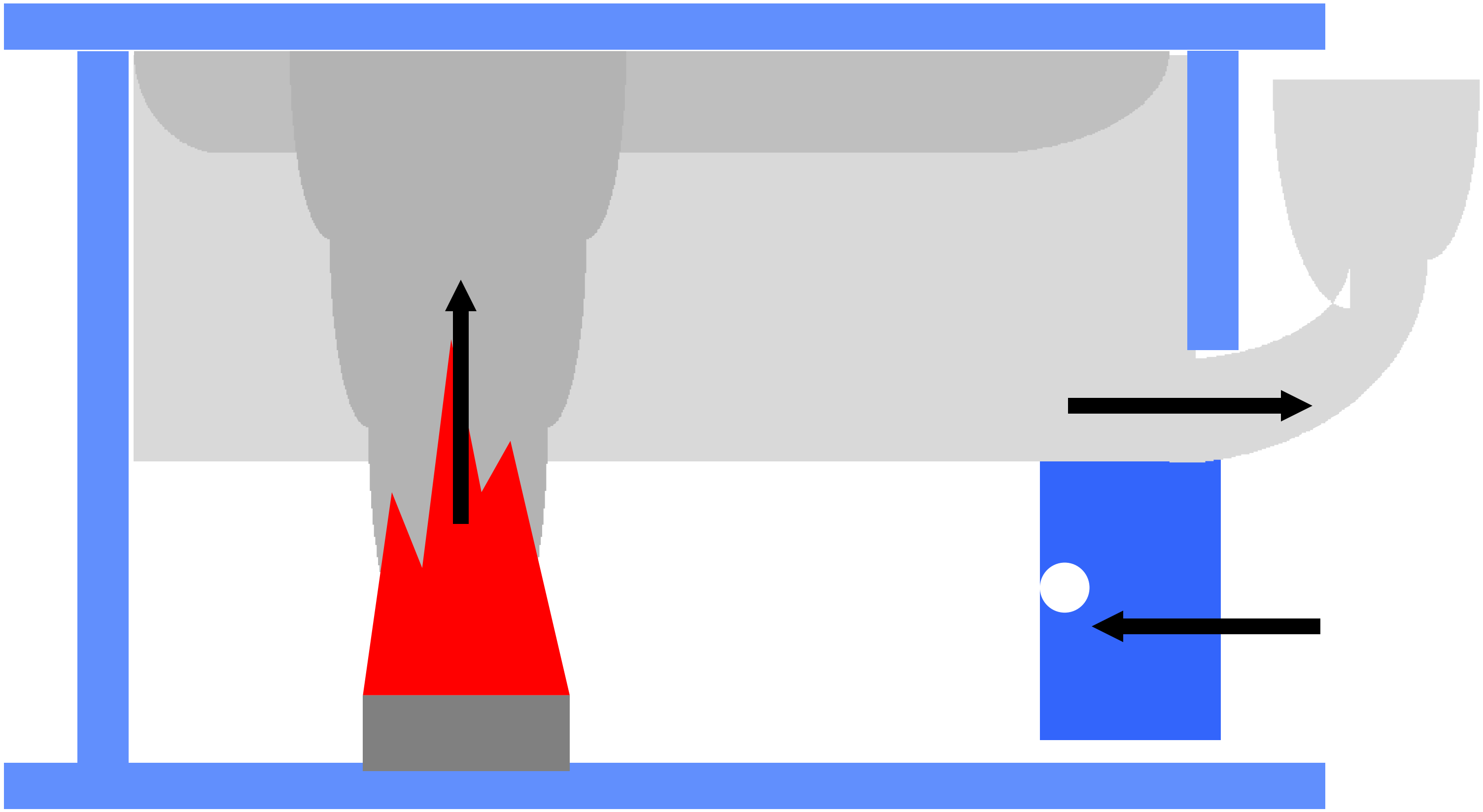


Mechanical ventilation

- Extraction $\dot{m}_i = \dot{m}_o + \dot{m}_{ext}$



Preflashover vented period



Energy balance

- Upper layer balance

$$\dot{Q}_f = \dot{Q}_l + \dot{Q}_c$$

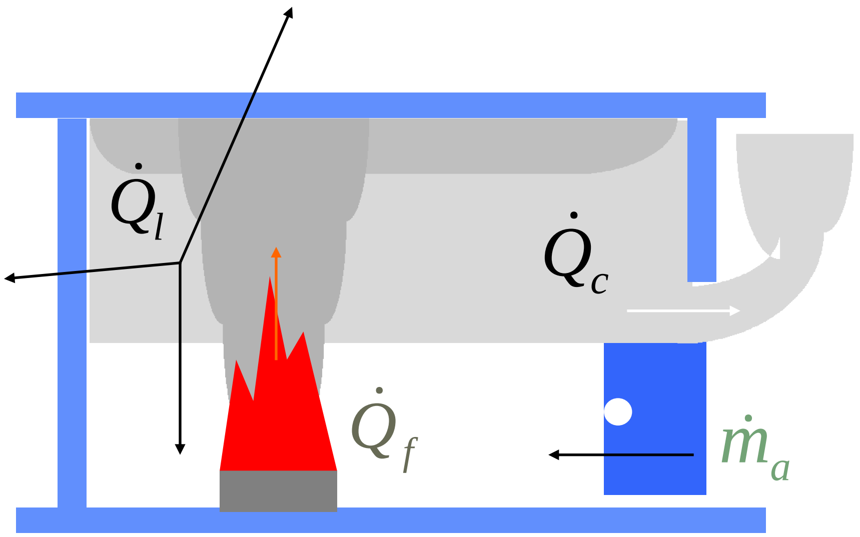
- Heat loss term

$$\dot{Q}_l = h_k A_s \Delta T$$

- Convective term

$$\dot{Q}_c = \dot{m}_a c_p \Delta T$$

- Solve for ΔT:



$$\Delta T = \frac{\dot{Q}_f}{\dot{m}_a c_p + h_k A_s} = \frac{\dot{Q}_{net}}{\dot{m}_a c_p}$$

The MQH correlation

- Dimensionless variables $\dot{m}_a \sim A_o \sqrt{H_o}$

$$\frac{\Delta T}{T_o} = \frac{\dot{Q}_f}{\dot{m}_a c_p T_o + h_k A_s T_o} = \frac{\dot{Q}_f / \dot{m}_a c_p T}{1 + \dfrac{h_k A_s}{\dot{m}_a c_p}}$$

$$\frac{\Delta T}{T_o} = f\left[\frac{\dot{Q}_f}{\sqrt{g}\,\rho_o c_p T_o A_o \sqrt{H_o}}, \frac{h_k A_s}{\sqrt{g}\,\rho_o c_p A_o \sqrt{H_o}}\right]$$

The MQH correlation

- Statistical correlation of the form:

$$\frac{\Delta T}{T_o} = C\left(\frac{\dot{Q}_f}{\sqrt{g}\rho_o c_p T_o A_o \sqrt{H_o}}\right)^N \left(\frac{h_k A_s}{\sqrt{g}\rho_o c_p A_o \sqrt{H_o}}\right)^M$$

- Over 100 sets of room fire data
  - Fuels: Gas, wood, plastics
  - Range of room sizes, thermal properties
  - Bias towards low fires in center of room

The MQH correlation

- Values for C, N and M from regression:

$$\frac{\Delta T}{T_o} = 1.63\left(\frac{\dot{Q}_f}{\sqrt{g}\rho_o c_p T_o A_o \sqrt{H_o}}\right)^{2/3}\left(\frac{h_k A_s}{\sqrt{g}\rho_o c_p A_o \sqrt{H_o}}\right)^{-1/3}$$

- For conventional values, this reduces to:

$$\Delta T = 6.85\left(\frac{\dot{Q}_f^2}{A_o\sqrt{H_o}h_k A_s}\right)^{1/3}$$

Heat transfer coefficient

- Early stage - transient semi-infinite solid

$$\dot{q}'' = \frac{1}{\sqrt{\pi}}\sqrt{\frac{k\rho c}{t}}(T_g - T_o) \sim \sqrt{\frac{k\rho c}{t}}(T_g - T_o)$$

- Late stage - steady one-dimensional slab

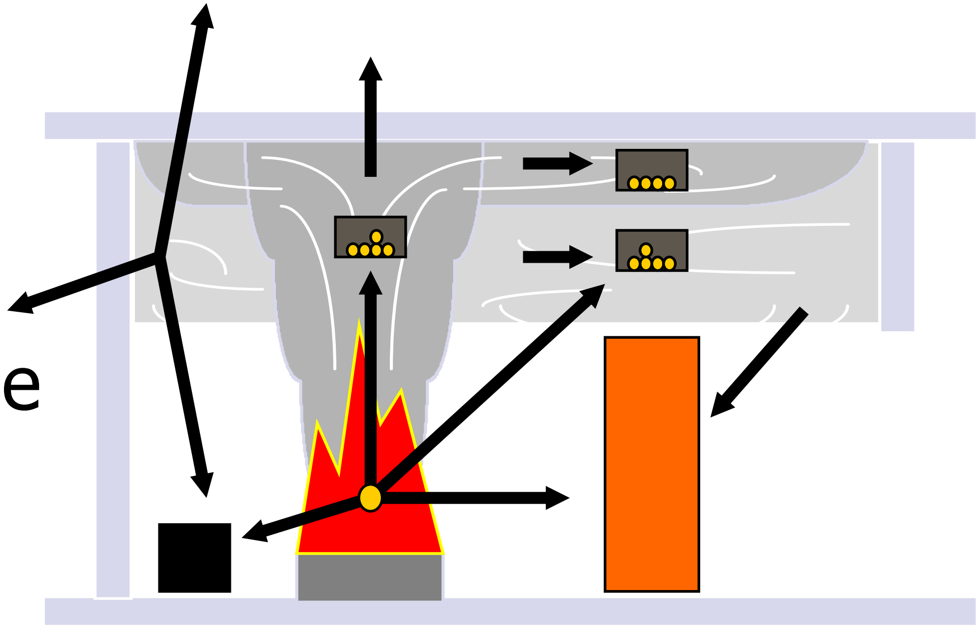
$$\dot{q}'' = \frac{k}{\delta}(T_g - T_o)$$

- Effective heat transfer coefficient

$$h_k = MAX\left(\sqrt{\frac{k\rho c}{t}}, \frac{k}{\delta}\right)$$

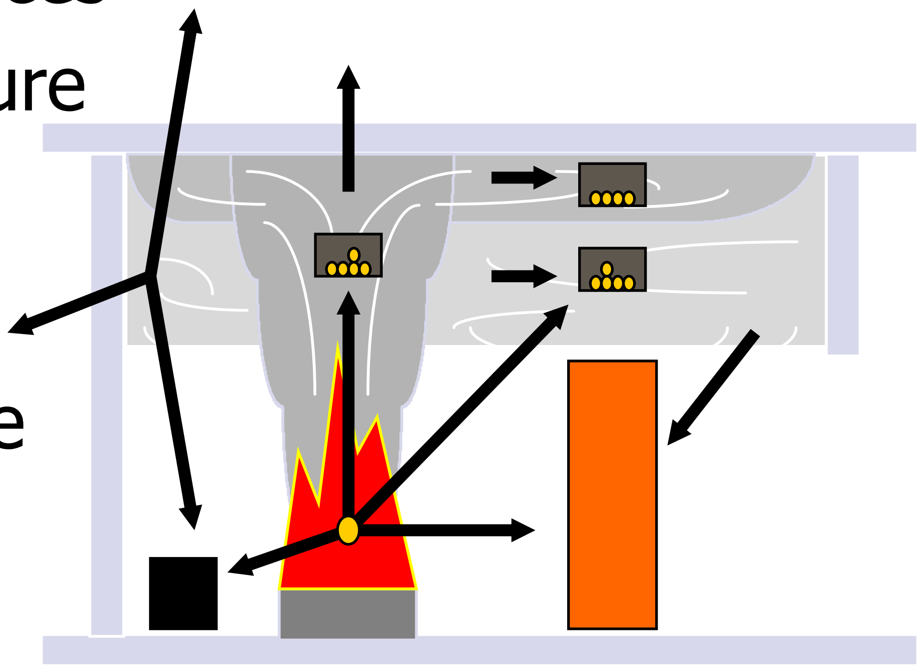
Boundaries

- Types
  - Walls / ceiling / floor
  - Columns / beams
- Issues
  - Heat transfer
    - Thermal inertia
  - Ignition / damage
  - Stability



Targets

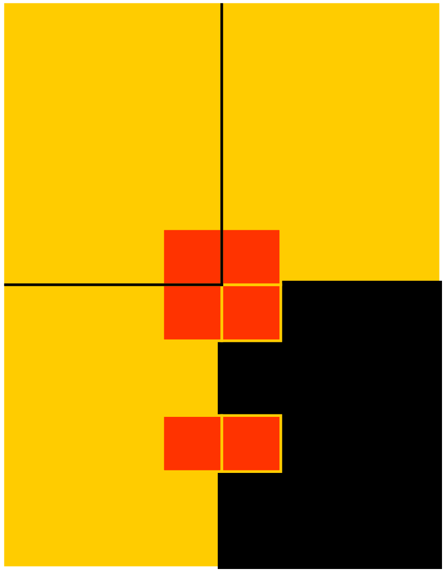
- Types
  - People (moving targets)
  - Fire protection devices
  - Equipment / structure
- Issues
  - Injury
  - Activation / damage
  - Operability



Thermal properties

MATERIAL	k [kW/m.K]	p [kg/m3]	cp [kJ/kg.K]	a [m2/s]	kpc
Aluminum (pure)	2.06E-01	2710	0.895	8.49E-05	5.00E+02
Concrete	1.60E-03	2400	0.75	8.89E-07	2.88E+00
Aerated concrete	2.60E-04	500	0.96	5.42E-07	1.25E-01
Brick	8.00E-04	2600	0.8	3.85E-07	1.66E+00
Concrete block	7.30E-04	1900	0.84	4.57E-07	1.17E+00
Cement-asbestos board	1.40E-04	658	1.06	2.01E-07	9.76E-02
Calcium silicate board	1.25E-04	700	1.12	1.59E-07	9.80E-02
Alumina silicate block	1.40E-04	260	1	5.38E-07	3.64E-02
Gypsum board	1.70E-04	960	1.1	1.61E-07	1.80E-01
Plaster board	1.60E-04	950	0.84	2.01E-07	1.28E-01
Plywood	1.20E-04	540	2.5	8.89E-08	1.62E-01
Chipboard	1.50E-04	800	1.25	1.50E-07	1.50E-01
Fiber insulation board	5.30E-05	240	1.25	1.77E-07	1.59E-02
Glass fiber insulation	3.70E-05	60	0.8	7.71E-07	1.78E-03
Expanded polystyrene	3.40E-05	20	1.5	1.13E-06	1.02E-03

Fires along walls and in corners

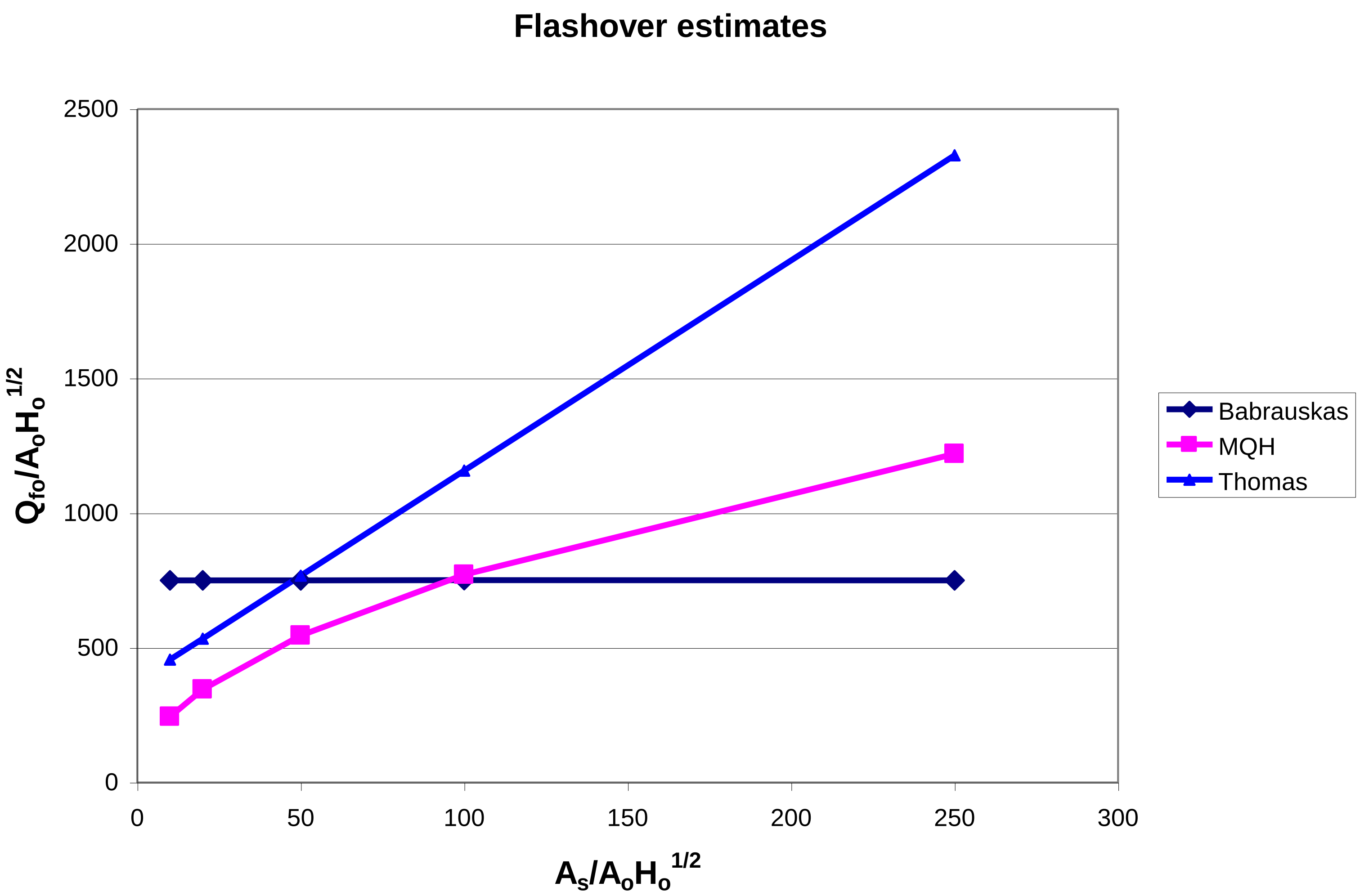


- Concept of reflection
  - Reduced entrainment rate
  - Higher temperatures
  - Longer entrainment height
- Mowrer and Williamson adjustment factors
  - Fires along walls $\Delta T = 1.3 \times \Delta T_{MQH}$
  - Fires in corners $\Delta T = 1.7 \times \Delta T_{MQH}$

Flashover estimates

- Babrauskas $\dot{Q}_{FO} = 750 A_o \sqrt{H_o}$
- MQH $\dot{Q}_{FO} = 610 \left(A_o \sqrt{H_o} h_k A_s \right)^{1/2}$
- Thomas $\dot{Q}_{FO} = 7.8 A_s + 378 A_o \sqrt{H_o}$
- Plot of $\dfrac{\dot{Q}}{A_o \sqrt{H_o}} = f\left(\dfrac{A_s}{A_o \sqrt{H_o}} \right)$

Flashover estimates



CFAST 6.3

- Model installer can be downloaded from:
  - https://code.google.com/p/cfast/
- Documentation can be downloaded from:
  - https://code.google.com/p/cfast/downloads/list
  - Includes tech / user manuals and validation report

CFAST examples

- Appendix A – Cabinet fire in main control room
- Appendix B – Cabinet fire in switchgear room
- Appendix D – MCC fire in switchgear room
- Appendix E – Transient fire in cable spreading room